JCAA/JG-PP No-Lead Solder Project:
-55ºC to +125ºC Thermal Cycle Testing Final Report

Rockwell Collins Advanced Manufacturing Technology Group

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Table of Contents

List of Figures

List of Tables

List of Appendixes

Abstract

The use of conventional tin-lead (Sn/Pb) solder in circuit board manufacturing is under ever-increasing political scrutiny due to environmental issues and new regulations concerning lead, such as the Waste Electrical and Electronic Equipment (WEEE) and the Restriction on Hazardous Substances (RoHS) Directives in Europe. In response to this, global commercial electronic manufacturers are initiating efforts to transition to lead-free assembly. Lead-free (Pbfree) materials may find their way into the inventory of aerospace and defense assembly processes under government acquisition reform initiatives. Any potential banning of lead compounds could reduce the supplier base and adversely affect the readiness of missions led by National Aeronautical Space Agency (NASA) and the Department of Defense (DoD). The Joint Council on Aging Aircraft (JCAA)/ Joint Group on Pollution Prevention (JG-PP) Pbfree Solder Project, a partnership between DoD, NASA and OEMs, was created to examine the reliability of component solder joints using various Pbfree solders when exposed to harsh environments representative of NASA and DoD operational conditions. This paper documents final results of the JCAA/JG-PP consortia -55ºC to +125ºC thermal cycle testing. The goal of testing was to generate reliability data for test boards that are representative of IPC Class III High Performance Electronic Products.

Background

Thermal cycle testing was conducted by Rockwell Collins Inc. for the JCAA/JG-PP No-Lead Solder Project. The JCAA/JG-PP Consortium is the first group to test the reliability of Pbfree solder joints against the requirements of the aerospace/military community.
The solder alloys selected for test were:

Sn3.9Ag0.6Cu (SAC) for reflow and wave soldering
Sn3.4Ag1.0Cu3.3Bi (SACB) for reflow soldering
Sn0.7Cu0.05Ni (SNIC) for wave soldering
Sn37Pb (SnPb) for reflow and wave soldering

Test vehicles were assembled using these solders and a variety of component types. Thermal cycle testing was then conducted on the test vehicles using a -55ºC to +125ºC temperature range in accordance with the IPC-9701 specification.

Objective

The objective of the study was to compare the solder joint integrity of selected Pbfree solder alloys to Sn63/Pb37 solder alloys for a -55ºC to +125ºC temperature range.

Procedures

Test vehicle

Figure 1 illustrates the test vehicle used in the thermal cycle testing; it was 14.5 inches wide by 9 inches high by 0.090 inches thick and contained 6 layers of 0.5 ounce copper. The test vehicle was designed to meet IPC-6012, Class 3, Type 3 requirements. Two different test vehicle laminates were selected for the testing program. The first laminate was FR4 per IPC-4101/26 with a minimum Tg of 170ºC with an immersion silver surface finish. This laminate was selected to represent "Manufactured" printed wiring assemblies that were designed for use in Pbfree soldering processes. A total of 119 "Manufactured" test vehicles were produced. The second laminate was FR4 per IPC-4101/21 with a minimum Tg of 140ºC with a hot air, solder leveled (HASL) surface finish. This laminate was selected to represent legacy ("Rework") printed wiring assemblies that were not specifically designed for Pbfree soldering processes. A total of 86 legacy ("Rework") test vehicles were produced.

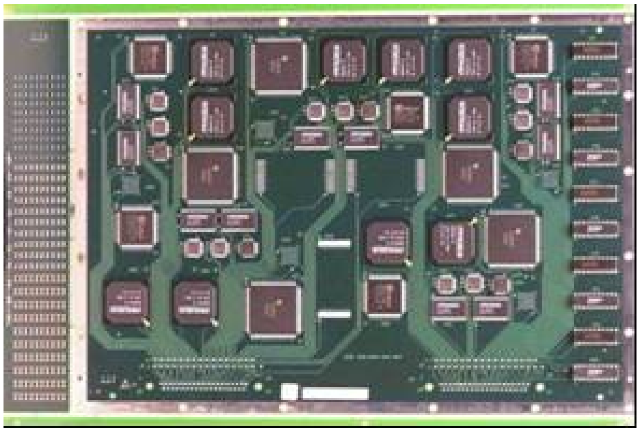


Figure 1 Test vehicle design

Test Components

A variety of component types and component surface finishes were included on the test vehicle. The ceramic leadless chip carrier (CLCC-20) and thin small outline package (TSOP-50) component types were selected due to industry acknowledged solder joint integrity issues in Class III High Performance electronic products. The dual in-line package (DIP-20) components were selected to represent plated thru hole technology. The plastic leaded chip carriers (PLCC-20), thin quad flat packs (TQFP-144 & TQFP-208), ball grid arrays (BGA-225), and surface mount capacitor/resistors were selected to represent surface mount technology. Table 1 lists the various component types and their surface finishes. The surface mount chip capacitors and resistors located on the test vehicle break-away edge coupon were tested separately from the other component types. The test data for the surface mount chip capacitors and resistors will be documented on in a future report.

Component Type	Component Finish
CLCC -20	SnPb
	SnAgCu
	SnAgCuBi
PLCC-20	Sn
TSOP-50	SnPb
	SnCu
TQFP-144	Sn
TQFP-208	NiPdAu
BGA-225	SnPb
	SnAgCu
DIP-20	Sn
	NiPdAu
0402 Capacitor	Sn
0805 Capacitor	Sn
1206 Capacitor	Sn
1206 Resistor	Sn

Table 1 Component types and finishes

Investigation Test Matrix

The investigation test matrix was designed to determine the solder joint thermal cycle reliability of Pbfree solder alloys as assembled on both the "Manufactured" and legacy ("Rework") test vehicles (Figure 2). In addition, a select number of components were reworked on the legacy ("Rework") test vehicles (Table 2) prior to thermal cycling to assess the impact of using lead free components and processes to repair circuit card assemblies designed for assembly with eutectic processes.

Legacy "Rework" Control Test Vehicles				
Location Number	Component Type	Qty Per Vehicle	Component Finish Before Rework	Component Finish After Rework
U25	TSOP 50	1	SnPb	SnPb
U12	TSOP 50	1	SnPb	SnPb
U57	TQFP 208	1	AuPdNi	AuPdNi
U3	TQFP 208	1	AuPdNi	AuPdNi
U18	PBGA 225	1	SnPb	SnPb
U4	PBGA 225	1	SnPb	SnPb
U59	PDIP 20	1	AuPdNi	AuPdNi
U23	PDIP 20	1	AuPdNi	AuPdNi

Legacy "Rework" Test Vehicles				
Location Number	Component Type	Qty Per Vehicle	Component Finish Before Rework	Component Finish After Rework
U25	TSOP 50	1	SnPb	SnCu
U12	TSOP 50	1	SnPb	SnCu
U57	TQFP 208	1	AuPdNi	AuPdNi
U3	TQFP 208	1	AuPdNi	AuPdNi
U18	PBGA 225	1	SnPb	SnAgCu
U4	PBGA 225	1	SnPb	SnAgCu
U59	PDIP 20	1	AuPdNi	AuPdNi
U23	PDIP 20	1	AuPdNi	AuPdNi

Table 2 Components reworked on the legacy ("Rework") test vehicles.

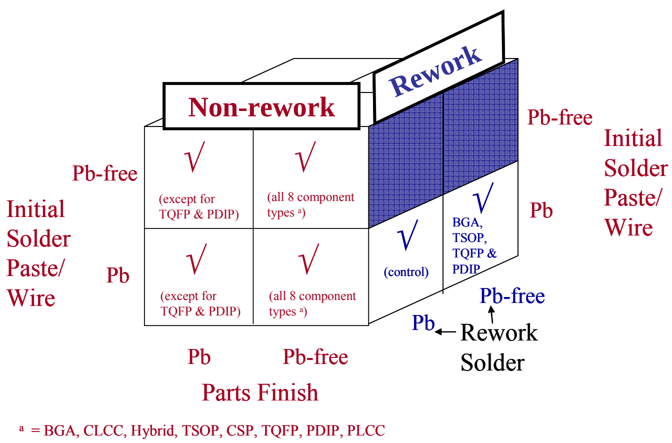


Figure 2 Test matrix

Test Vehicle Assembly

The 205 test vehicles (119 "Manufactured" and 86 legacy ("Rework")) were assembled at the BAE Systems Irving Texas facility. A detailed description of the specific tin/lead and Pbfree soldering processes was presented in an earlier publication [1]. The solder joint quality of all test vehicles was confirmed with X-ray inspection and visual inspection in accordance with the IPC-JSTD-001/IPC-A-610 specifications.

Thermal Cycle Parameters and Methodology

The temperature cycle range used in the investigation was -55ºC to +125ºC with a 30 minute dwell at the high temperature extreme and a 10 minute dwell at the low temperature extreme. A maximum temperature ramp of 10°C/minute was used in the testing. The continuity of the components was continuously monitored throughout thermal cycle testing by an event detector in accordance with the IPC-9701 specification, with each component treated as a single resistance channel. An 'event' was recorded if the resistance of a channel exceeded 300 Ω for more than 0.2 µsec. A failure was defined when a component either:

- Recorded an event for 15 consecutive cycles,
- Had five consecutive detection events within 10% of current life of test, or
- Became electrically open.

Once a solder joint was designated a failure, the event detection system software excluded it from the remainder of the test. Detailed temperature profiling was conducted prior to the beginning of the thermal cycle conditioning to insure that each test vehicle was subjected to uniform, consistent exposure to the test chamber temperatures. In the Rockwell Collins consortia testing effort, a total of 15 "Manufactured" test vehicles and 15 legacy ("Rework") test vehicles were placed in the chamber. Figure 3 illustrates the thermal cycle temperature profile for the -55ºC to +125ºC testing and the resulting measured test vehicle temperatures with a time lag due to thermal inertia. Figure 4 illustrates the test vehicles positioned in the -55ºC to +125ºC test chamber.

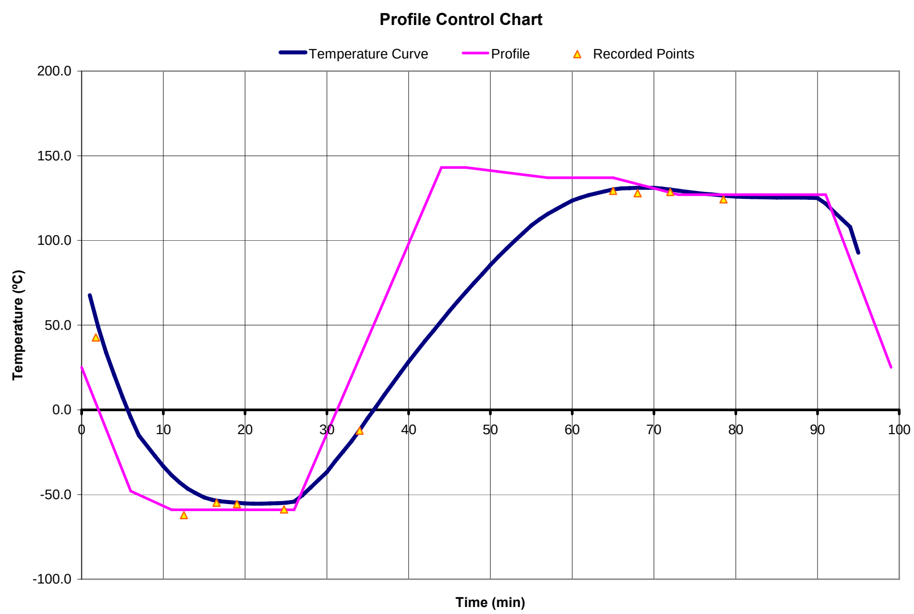


Figure 3 Thermal cycle profile for the -55ºC to +125ºC conditioning

Figure 4 Test vehicles loaded into the -55ºC to +125ºC test chamber

Test Results – Statistical Analysis

The test vehicles completed a total of 4743 thermal cycles during the 12 month test duration. Table 3 lists the final component population failure rates after completing 4743 thermal cycles. A statistical analysis for each component type was completed with the following sections summarizing the results for each specific component style.

Component Type	Total Failures	Total Population	Percent Failed
BGA 225	257	300	85.7
CLCC 20	300	300	100
PDIP 20	24	300	8
PLCC 20	8	150	5.3
TQFP 144	136	150	90.7
TQFP 208	110	150	73.3
TSOP 50	296	300	98.7

Table 3 Component population failure rates after 4743 thermal cycles

Ball Grid Array (BGA-225) Results

By the end of testing, 85.7% (257 of 300) of the BGA component total population had failed. On the "Manufactured" test vehicles (170ºC Tg), both the SACB and SAC solder alloys had better performance that the SnPb solder alloy. The Weibull plot (Figure 5) shows two early BGA SAC/SAC, i.e. SAC solder/SAC solderpaste, failures that resulted in a significantly lower Weibull slope for this combination compared to the others. Due to these two early failures, the SAC/SAC combination had a much lower first failure than the other combinations. Also, the Pbfree solders with SnPb solderpaste exhibited lower (SAC/SnPb) or essentially the same (SACB/SnPb) reliability as SnPb/SnPb components. However, the average and characteristic lives of the Pbfree (SAC or SACB solder with SAC surface finish) BGA's were 30-50% higher than of the Sn/Pb components (Figure 6). On the legacy ("Rework") test vehicles (140ºC Tg), the reworked SnPb solderpaste/SAC solderball mixed metallurgy combination had a much lower Weibull slope than the other solderpaste/solderball combinations (Figure 7). In other words, the failures were distributed over a much wider range of thermal cycles, indicating that the reworked SAC solder joints were not as consistent as those made with other material combinations.

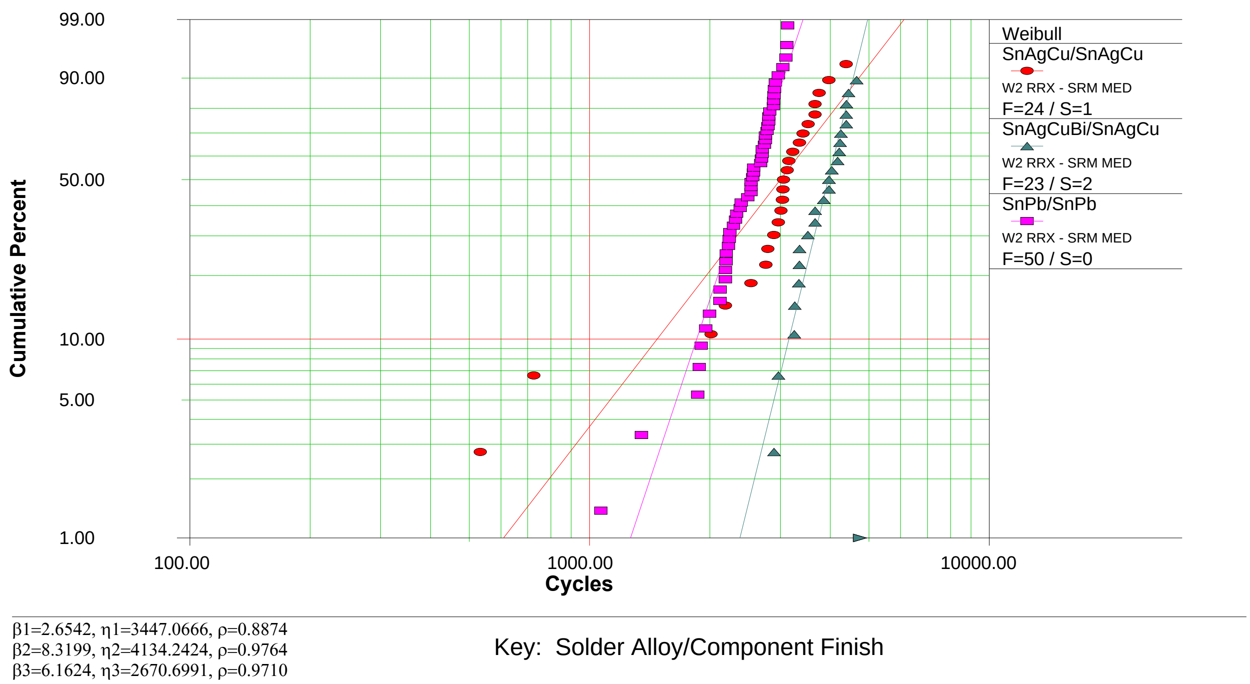
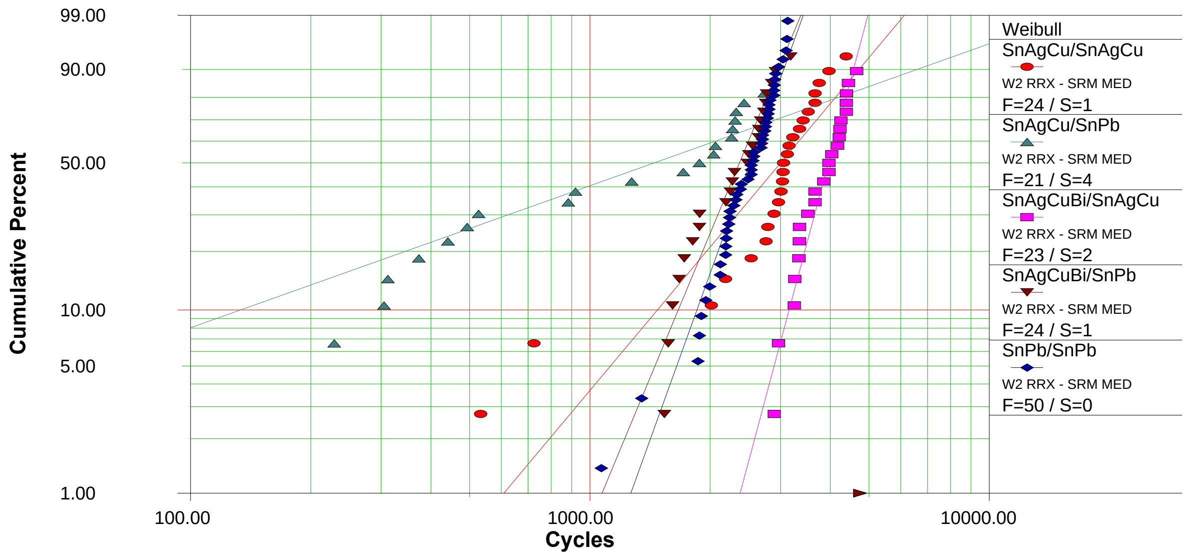


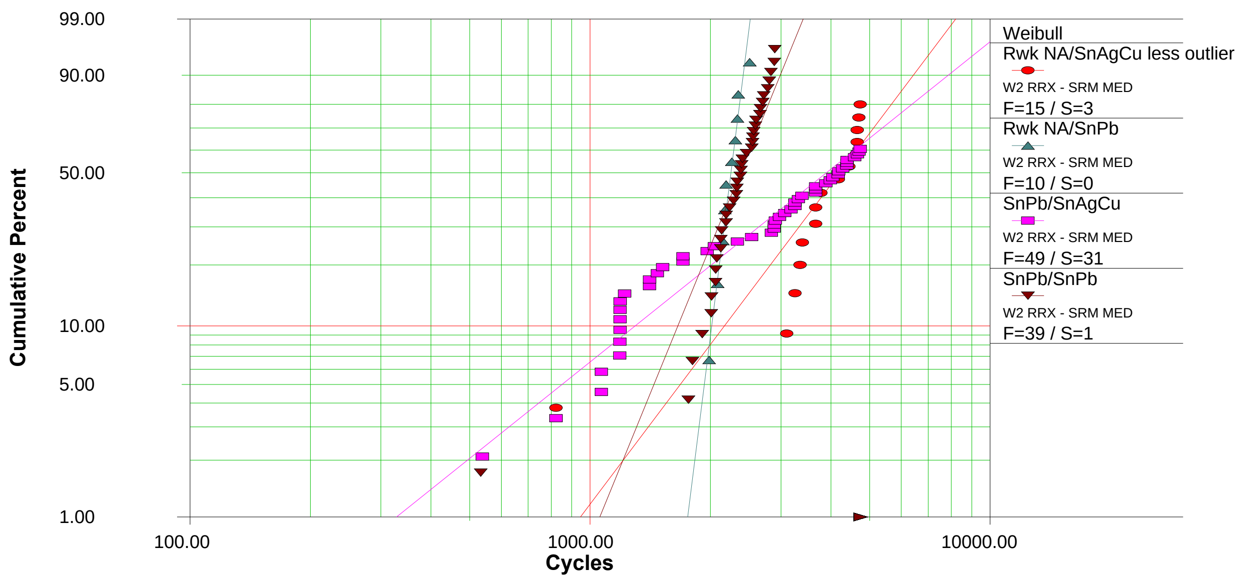
Figure 5 BGA-225 Pbfree versus SnPb test results for the "Manufactured" test vehicles (170C Tg)



β1=2.6542, η1=3447.0666, ρ=0.8874
β2=0.7906, η2=2301.0183, ρ=0.9262
β3=8.3199, η3=4134.2424, ρ=0.9764
β4=5.3473, η4=2536.9533, ρ=0.9649
β5=6.1624, η5=2670.6991, ρ=0.9710

Key: Solder Alloy/Component Finish

Figure 6 BGA-225 all combinations test results for the "Manufactured" test vehicles (170C Tg)



β1=2.8360, η1=4793.8892, ρ=0.8559
β2=17.0339, η2=2299.0505, ρ=0.9799
β3=1.7117, η3=4827.3427, ρ=0.9768
β4=5.2327, η4=2548.4173, ρ=0.8368

Key: Solder Alloy/Component Finish

Figure 7 BGA-225 all combinations test results for the legacy ("Rework") test vehicles (140C Tg)

Ceramic Leadless Chip Carrier (CLCC-20) Results

The CLCC-20 components were one of only two component types that experienced 100% population failure during this testing. The CLCC-20 components were included on the test vehicles because of their poor reliability track record on electronic assemblies used in harsh environments. Industry data [2] has demonstrated that the CLCC component style undergoes solder joint integrity degradation under IPC Class 3 use environments due to coefficient of thermal expansion (CTE) mismatch with the printed wiring assembly. CLCC-20 components with three different termination finish/solderpaste alloy combinations (SAC/SAC, SACB/SACB, SnPb/SnPb) were tested and the results showed statistically significant differences in thermal cycle reliability. The following Weibull plots summarize the CLCC-20 thermal cycle test results. On the "Manufactured" test vehicles (170ºC Tg), the characteristic life of the SAC solder alloy was approximately 200 cycles less than the SACB or SnPb solder alloys (**Figure 8**). On the legacy ("Rework") test vehicles (140ºC Tg), the components with SnPb solder had nearly twice the fatigue life of either the SAC and SACB components (Figure 9). Note that the reliability of the CLCC-20 components with SnPb solder was essentially the same whether they were on the "Manufactured" or the legacy ("Rework") test vehicles (Figure 10).

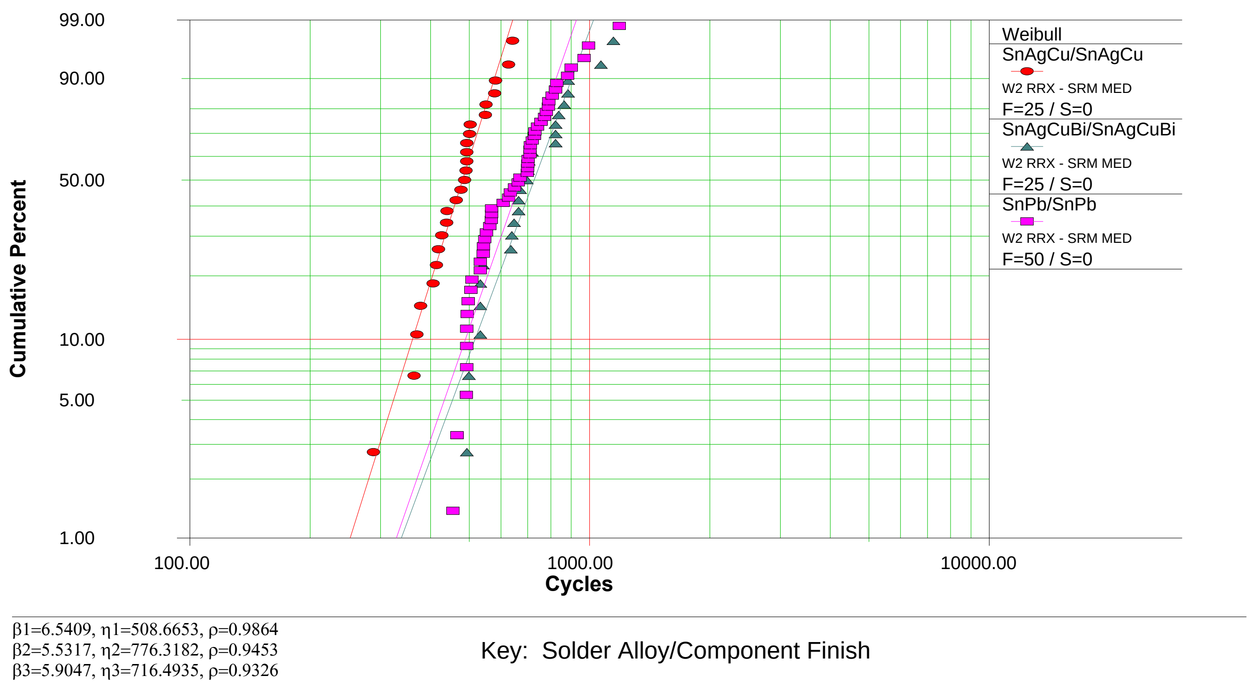


Figure 8 CLCC-20 test results for the "Manufactured" test vehicles (170ºC Tg)

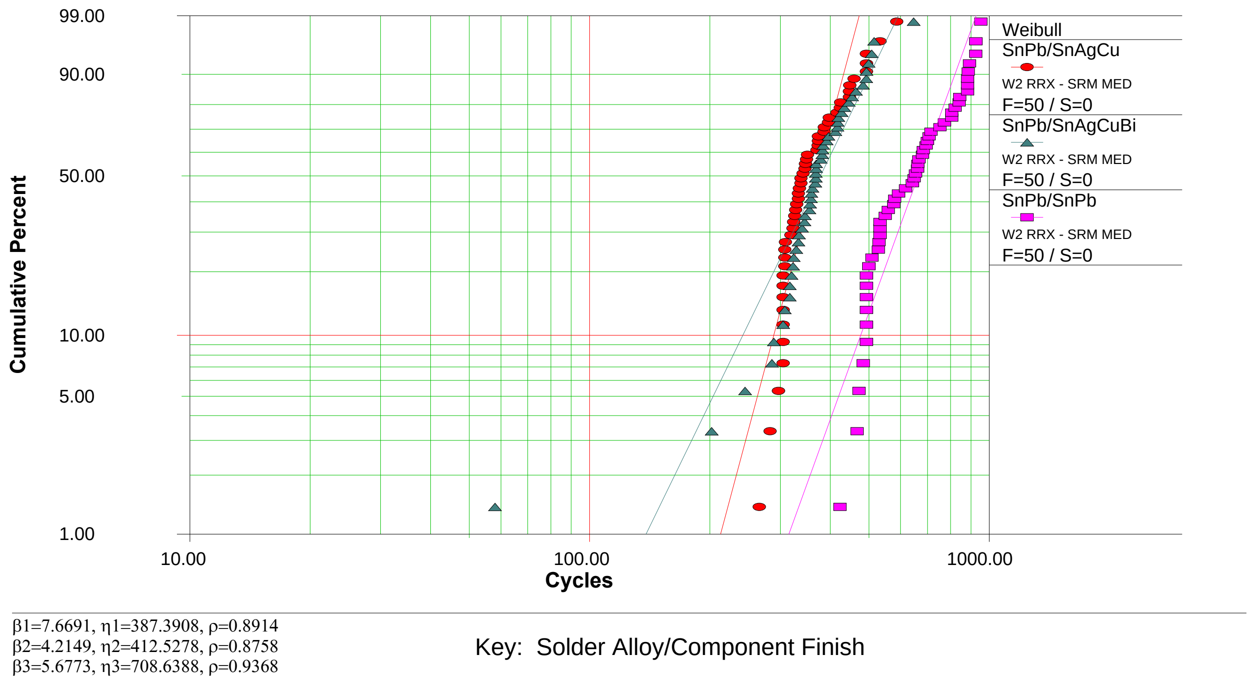


Figure 9 CLCC-20 test results for the legacy ("Rework") test vehicles (140°C Tg)

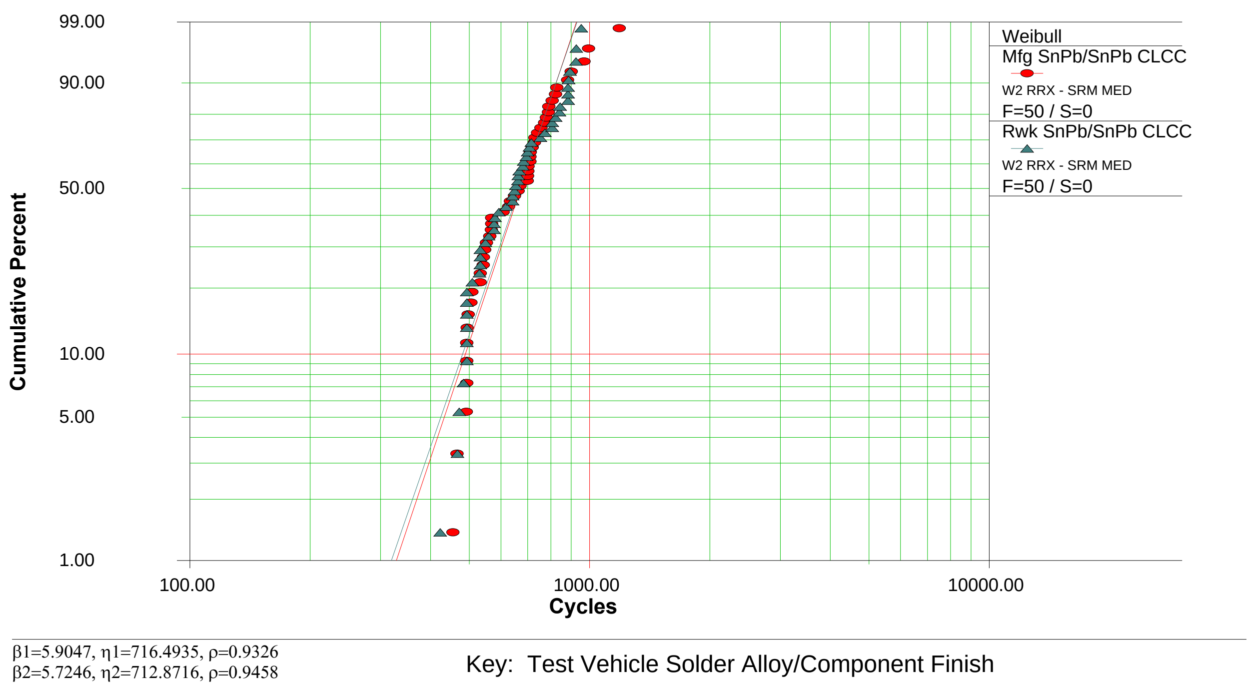


Figure 10 Comparison of CLCC-20 components with SnPb solder on “Manufactured” and legacy (“Rework”) test vehicles

Thin Quad Flat Pack (TQFP-144 and TQFP-208) Results

The TQFP-144 components failed 90.7% (136 of 150) of the total test population after 4743 thermal cycles. These tests included all three solder pastes (SAC, SACB, and SnPb) with only one surface finish (Sn). Figure 11 illustrates the test results. On the “Manufactured” test vehicles (170ºC Tg), the TQFP-144 components assembled with SACB solderpaste had ~40% better reliability than the SnPb components. The components assembled with SAC had a similar characteristic life (N63) to those with the other solderpaste, but a significantly lower Weibull slope. This result again suggests that the SAC solder joints were less consistent than those assembled with either SnPb or SACB. TQFP-144 components assembled with SnPb on legacy (“Rework”) test vehicles (Figure 12) had virtually the same slope (consistency) as parts on “Manufactured” boards, but lower characteristic life (1977 vs. 2672).

The TQFP-208 components failed 73.3% (110 of 150) of the total test population after 4743 thermal cycles. On the “Manufactured” test vehicles (170ºC Tg), there was at least one early failure for all three solder alloys investigated. Except for two early failures, the SAC TQFP-208 components had similar reliability behavior as the SnPb components, i.e. the slopes and characteristic life are similar (Figure 13). Typically, a Weibull slope of less than 1.0, as in the case of the TQFP-208 components with SACB, is considered to indicate infant mortality failures. This indicates that if consistent solder joints can be created with SACB, these parts would be more reliable than with SnPb.

On the legacy (“Rework”) test vehicles (140ºC Tg), the reworked TQFP-208 components had significantly shorter life (> 700 thermal cycles) than the non-reworked TQFP-208 components (Figure 14). Figure 15 illustrates the poor performance of the reworked SACB solder alloy in comparison to SAC and SnPb. A review of the TQFP rework protocol revealed a likely cause of poor reworked components performance – the TQFP component was the last of a group of 4 components reworked in a closely grouped test vehicle region. The TQFP component pads were oxidized during the replacement soldering of the other three components thus impacting the TQFP rework final solder joint integrity.

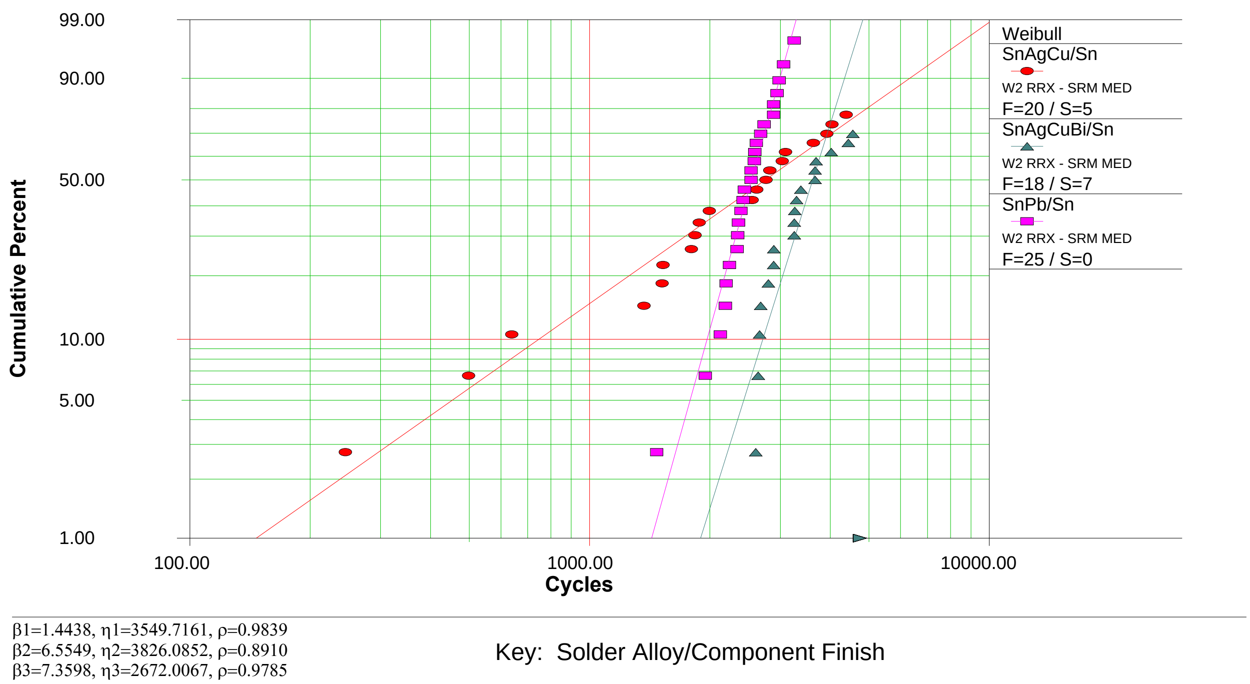


Figure 11 TQFP-144 Pbfree versus SnPb test results for “Manufactured” test vehicles (170ºC Tg)

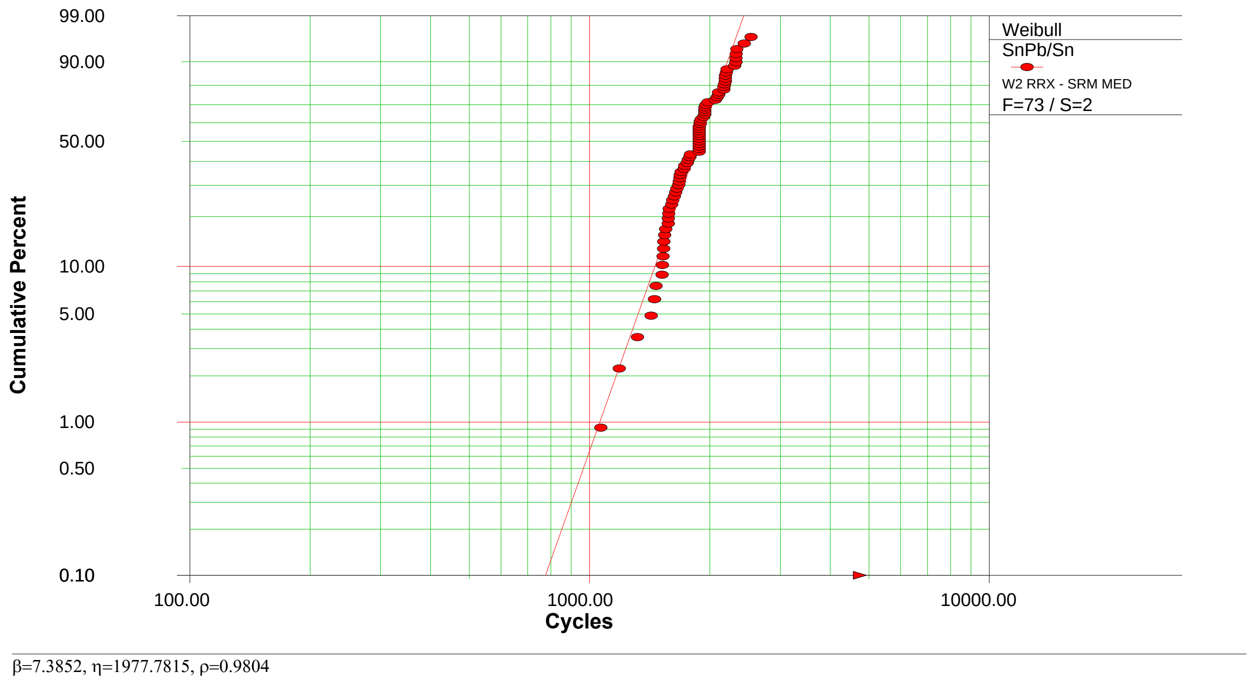


Figure 12 TQFP-144 test results for legacy ("Rework") test vehicles (140ºC Tg)

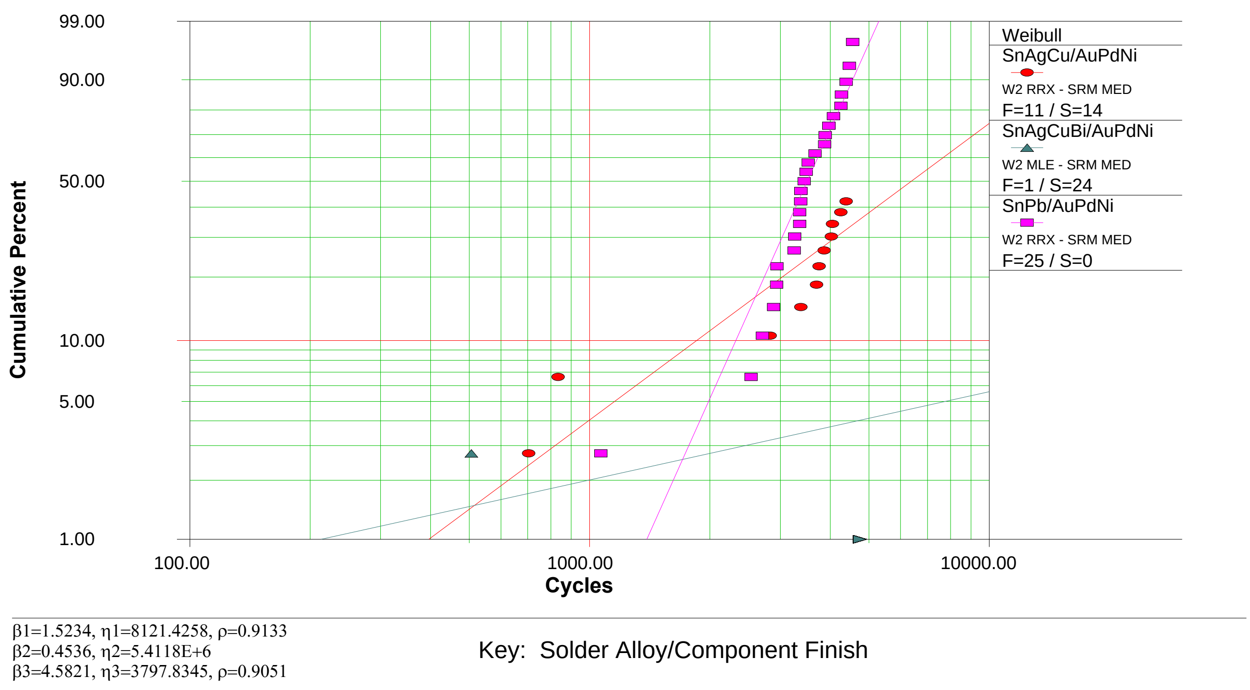


Figure 13 TQFP-208 all combination results for "Manufactured" test vehicles (170ºC Tg)

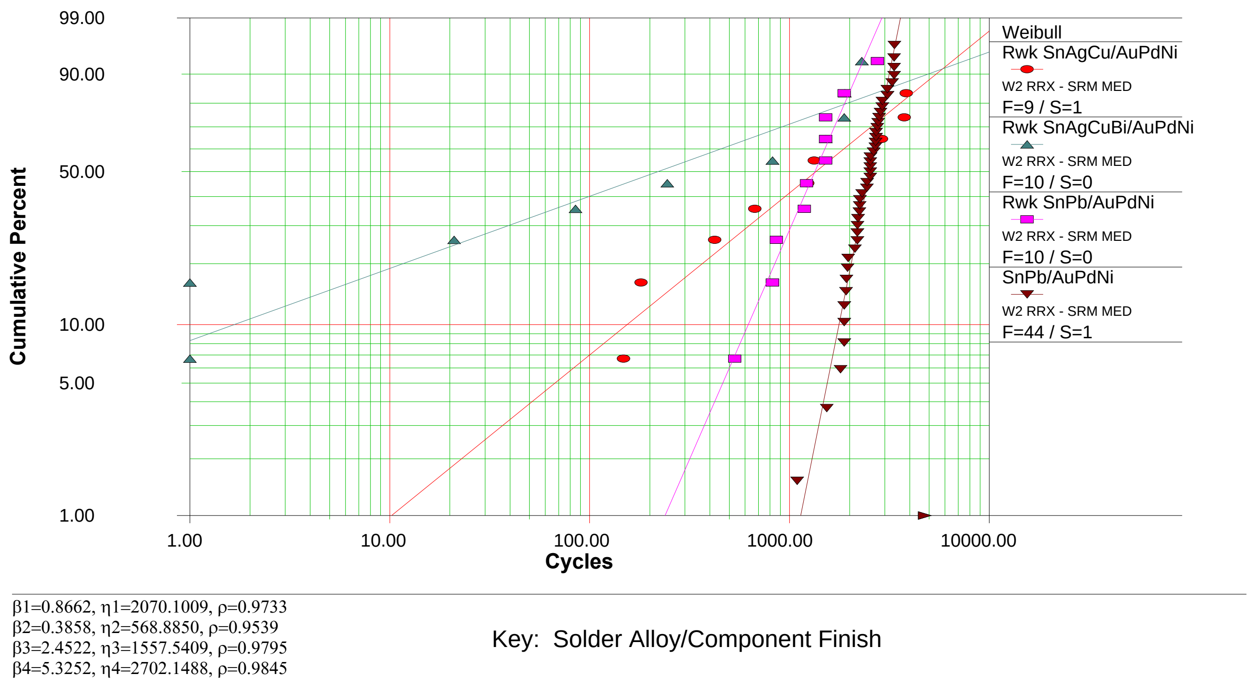


Figure 14 TQFP-208 all combination results for legacy ("Rework") test vehicles (140°C Tg)

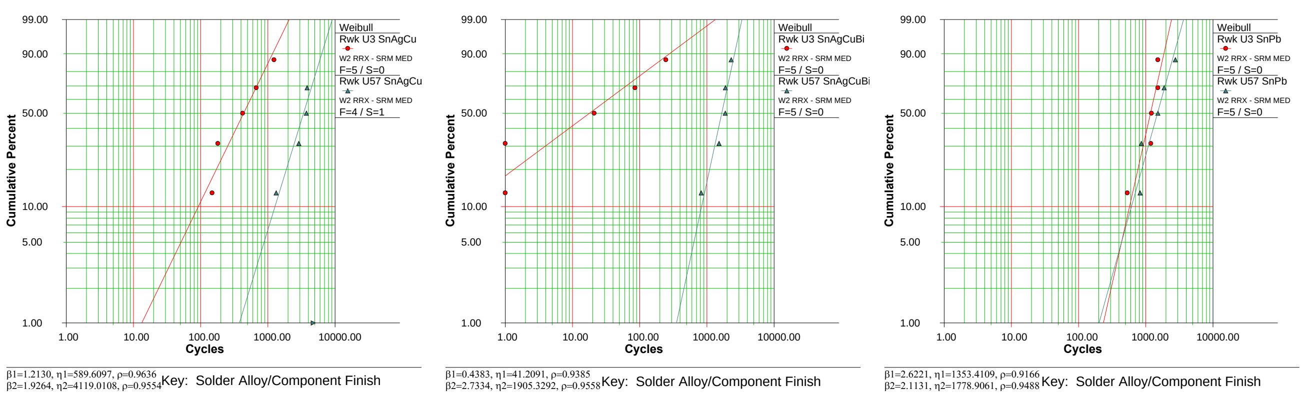


Figure 15 TQFP-208 Component U3 Versus Component U57 Comparison

SAC (left), SACB (Center), SnPb (right) for legacy ("Rework") test vehicles (140°C Tg)

Thin Small Outline Package (TSOP-50) Results

The TSOP-50 components also experienced 100% population failure by the end of testing. As with the CLCC components, industry data [3] has demonstrated that the TSOP component style undergoes significant solder joint integrity degradation during Class 3 level thermal cycling due to CTE mismatch. The TSOP components used in this testing had two different lead finishes (SnCu and SnPb) and were assembled with three solderpaste alloy combinations (SnPb, SAC, SACB). Figure 16 and Figure 17 illustrate the TSOP thermal cycle reliability test results. The TSOP components assembled on "Manufactured" test vehicles with SnPb and SAC solderpaste had essentially the same reliability regardless of surface finish (SnCu or SnPb). However, when SACB solderpaste was used, the surface finish had a significant effect. SACB solder with SnPb surface finish had significantly poorer reliability while SACB with SnCu finish had significantly better reliability than the other combinations (Figure 17). On the legacy ("Rework") test vehicles, the SAC/SnCu and SnPb/SnCu solderpaste/surface finish combinations had essentially the same reliability as SnPb/SnPb components while SACB/SnCu and reworked SnPb/SnPb components had somewhat lower reliability (Figure 18).

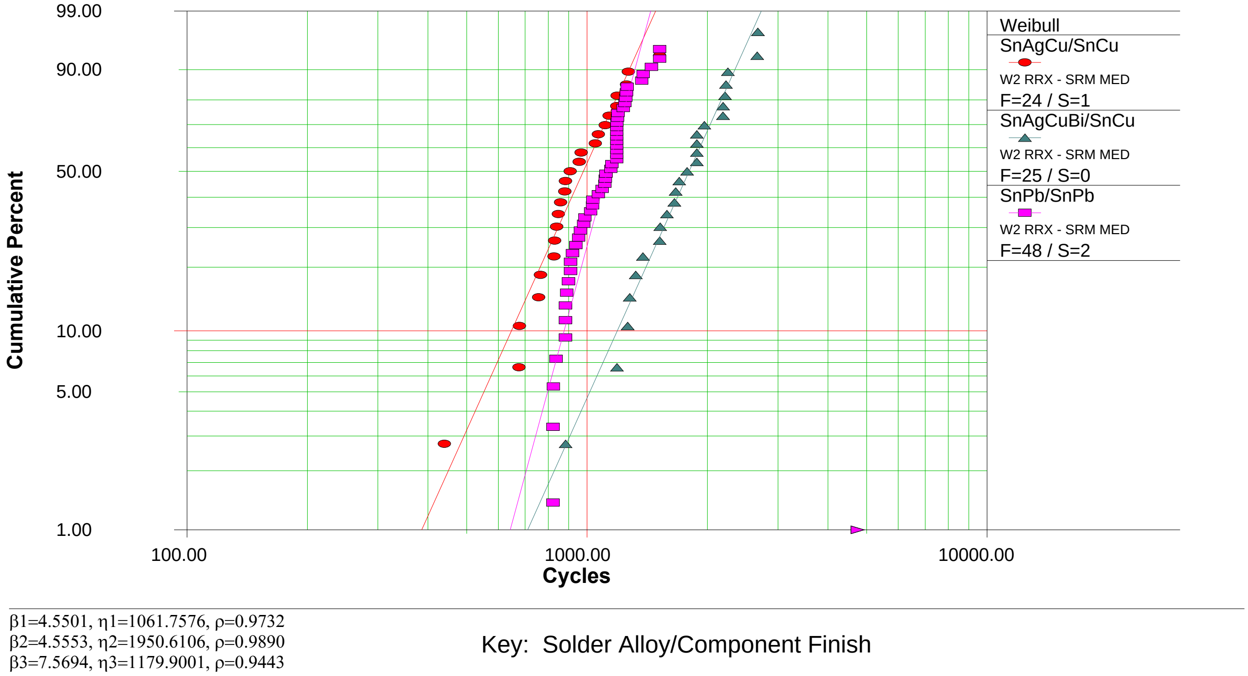
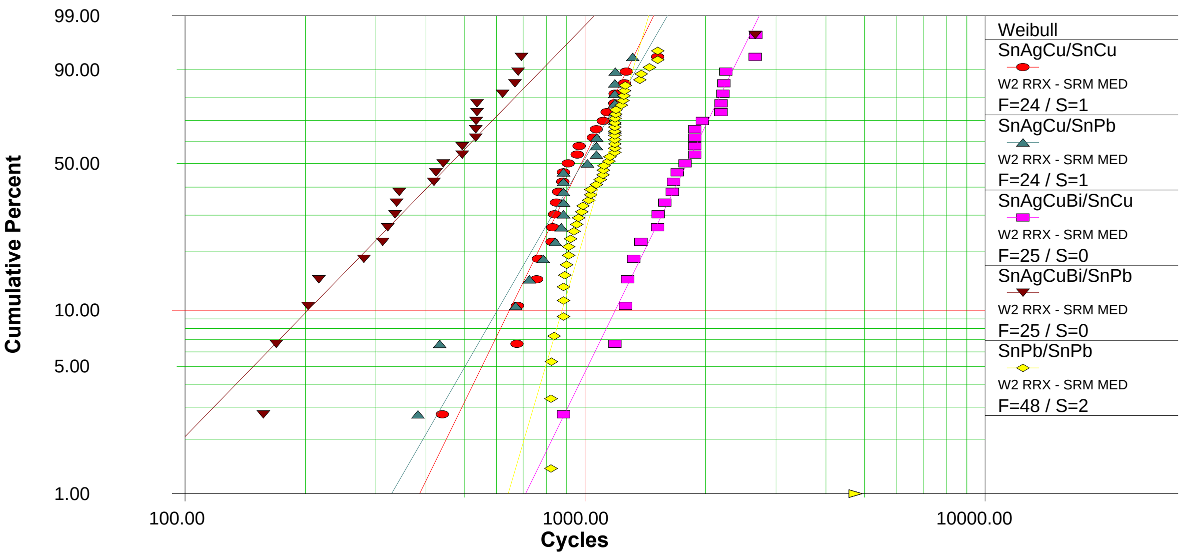


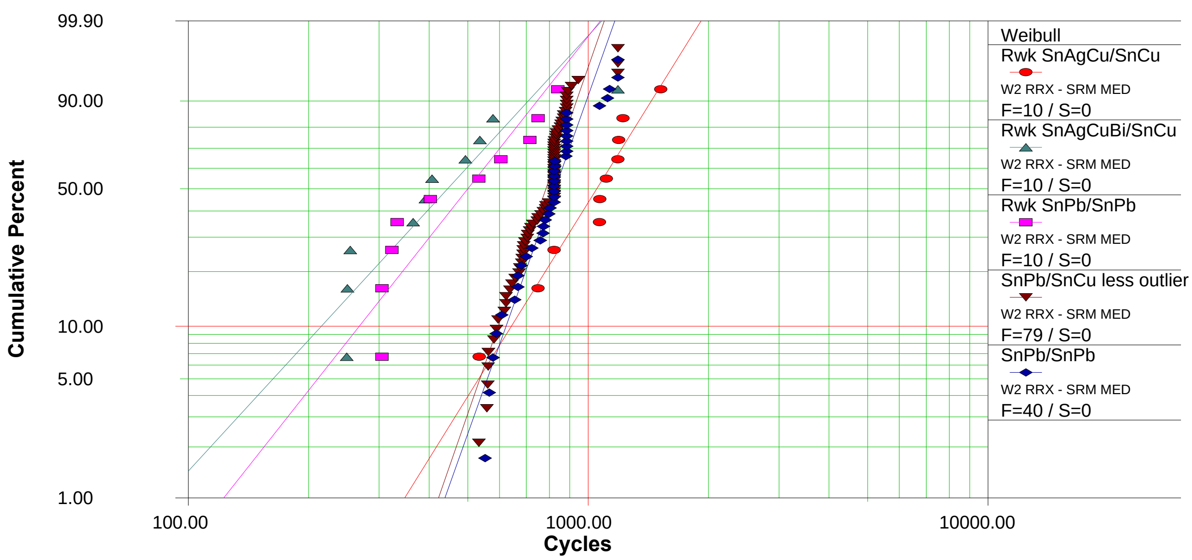
Figure 16 TSOP-50 Pbfree versus SnPb test results for "Manufactured" test vehicles (170°C Tg)



β1=4.5501, η1=1061.7576, ρ=0.9732
β2=3.8599, η2=1082.2162, ρ=0.9642
β3=4.5553, η3=1950.6106, ρ=0.9890
β4=2.2892, η4=542.1344, ρ=0.9096
β5=7.5694, η5=1179.9001, ρ=0.9443

Key: Solder Alloy/Component Finish

Figure 17 TSOP-50 all combinations test results for "Manufactured" test vehicles (170ºC Tg)



β1=3.8278, η1=1157.2025, ρ=0.9742
β2=2.5889, η2=513.0631, ρ=0.8972
β3=3.0130, η3=565.3405, ρ=0.9195
β4=6.8469, η4=827.4517, ρ=0.9547
β5=6.6749, η5=873.4001, ρ=0.9541

Key: Solder Alloy/Component Finish

Figure 18 TSOP-50 all combinations test results for the legacy ("Rework") test vehicles (140ºC Tg)

Dual In-line Package (DIP-20) Results

The DIP-20 components failed 8% (24 of 300) of the total test population after 4743 thermal cycles. The low component failure totals made the creation of Weibull plots meaningless for either the “Manufactured” or legacy (“Rework”) test vehicles. Each solderpaste/surface finish combination for the DIP-20 components experienced at least one failure before 1500 thermal cycles but no more than 2 failures by the end of testing at 4743 cycles. This, along with the calculated Weibull slopes of ~1 or less, indicates that these failures were likely due to infant mortality. The low overall failure rate of the DIP-20 components of 8% is indicative of the good reliability of that packaging style. However, the relatively consistent early failure trend (5 of the 6 combinations had a failure by 900 cycles) does demonstrate that there can be challenges in achieving 100% manufacturing consistency.

Plastic Leaded Chip Carrier (PLCC-20) Results

The PLCC-20 components failed 5.3% (8 of 150) of the total test population after 4743 thermal cycles. The low component failure totals made the creation of Weibull plots meaningless for either the “Manufactured” or legacy (“Rework”) test vehicles. The lack of failures reflects the overall good performance of the PLCC-20 component type.

Plated Thru Holes Results

Each test vehicle contained 63 total components resulting in the opportunity to include one plated thru hole circuit as the 64th channel on each connector of the event detection system. Although the inclusion of the 30 plated thru holes is not a statistically valid sampling population, the data provide a trend indication of plated thru hole interaction with the various soldering processes. Only two of the 30 plated thru holes failed – a plated thru hole on a SnPb soldered, legacy (“Rework”) test vehicle failed after 1779 cycles, and a plated thru hole on a SAC soldered, “Manufactured” test vehicle failed after 2568 cycles. The failure trend is encouraging, but additional investigation of the integrity impact resulting from the interaction of test vehicle structures (e.g. plated thru holes, traces) and Pbfree soldering processes needs to be completed before the true reliability trends can be fully understood.

The Appendices contain summary/comparison tables of the N1, N10 and N63 statistical analysis for each component on the test vehicles and all of the alloy specific Weibull plots generated from the statistical analysis.

Test Results – Physical Failure Analysis

In addition to conducting statistical analysis to determine the solder alloy/component finish solder joint thermal cycle fatigue life, extensive failure analysis was conducted. The following sections summarize each of the physical phenomena investigated during the failure analysis effort.

Failure Analysis – Tin Pest

Pure Sn is one of a number of elements which can undergo an allotropic change, transforming from β-Sn (white Sn) into α-Sn (gray Sn). This allotropic transformation of white Sn (metallic, body centered tetragonal lattice) into gray Sn (semi-conducting, diamond cubic lattice) occurs at 13.2°C. There is a 21% increase in volume resulting from this change in crystal structure [4]. This large volume change results in reducing the solid form into a powder form (Figure 19).

Figure 19 Allotropic tin transformation from Sweatman paper [5]

All 30 test vehicles were visually inspected at 10X magnification for indications of the allotropic transformation. No instances of transformation were observed.

Failure Analysis – Tin Whiskers

Tin whiskers are a topic of critical concern to the aerospace and military electronics sector. Extensive industry investigations [6] and industry specification [7] creation efforts are currently being undertaken. Tin whiskers are single crystal filament structure that extrude from tin surfaces and can cause electrical failure of printed wiring assemblies. Other metals such as zinc and cadmium have also been shown to produce whiskers [8]. The specific root cause parameter set that leads to whisker growth is not yet fully understood by the electronic industry. Each component on the thermal cycle test vehicles was examined for the presence of tin whiskers under a minimum of 100X magnification. The surface mount TSOP-50, TQFP-144, PLCC-20, and the plated thru hole DIP-20 components were the primary focus of the examinations.

Figure 20 thru Figure 24 illustrates typical tin whiskers found on the TSOP-50 components with SnCu surface finish. This TSOP-50 component was from the legacy ("Rework") test vehicle. It was originally reflow soldered with a SnPb solder alloy and then manually reworked with a SAC solder alloy as part of the overall rework impact segment of the investigation test matrix (Figure 2). Tin whiskers were found on lead surfaces that were not soldered (the upper knees of the component leads and lead faces) and would be characterized as dense fields with a "worm-like" appearance. SEM EDX analysis was used to confirm that the whiskers were comprised of tin (Figure 25: note gold (Au) presence due to SEM preparation procedure).

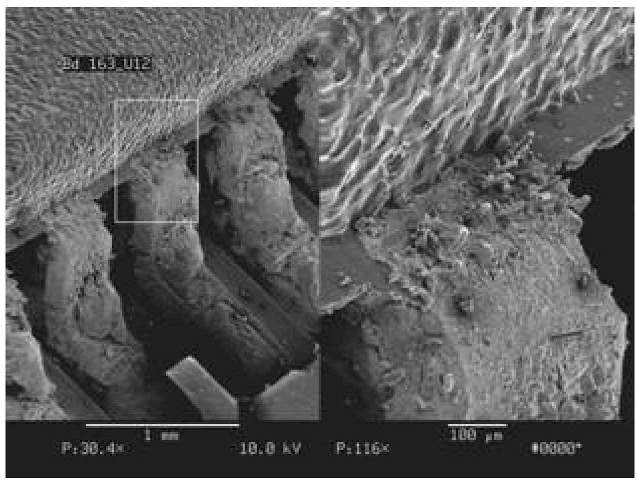


Figure 20 SEM image of TSOP component with SnCu surface finish showing tin whiskers on upper knee of lead

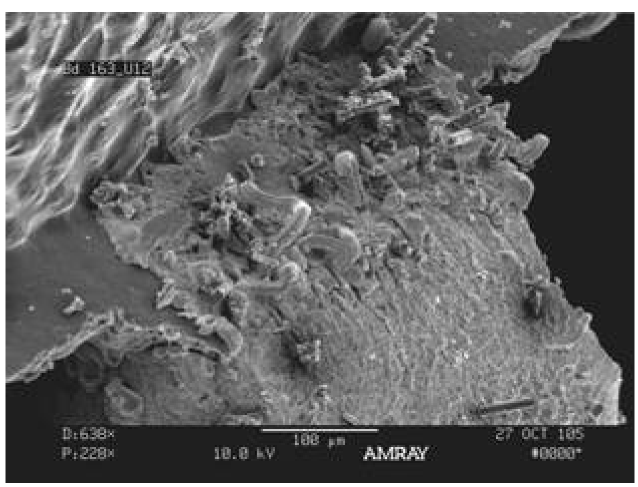


Figure 21 SEM image of TSOP component with SnCu surface finish showing tin whiskers on upper knee of lead

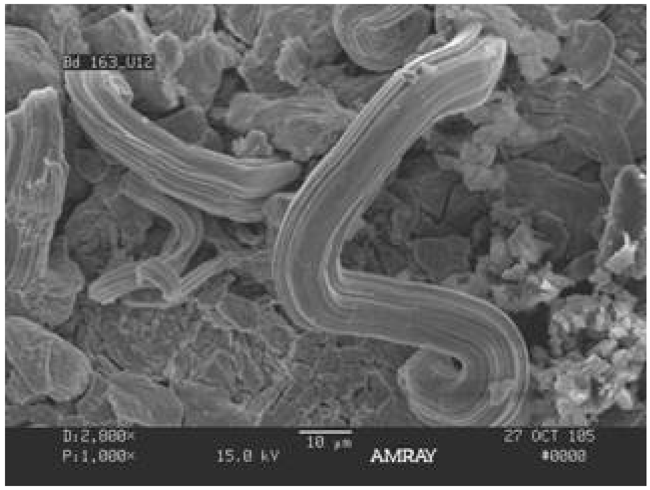


Figure 22 SEM image of TSOP component with SnCu surface finish showing tin whisker on upper knee of lead

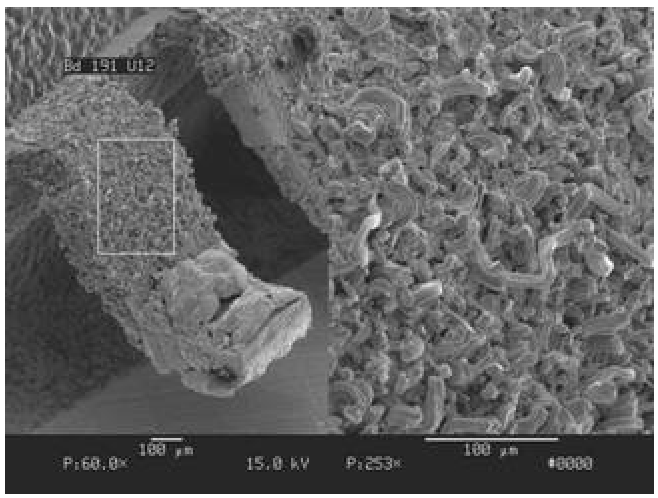


Figure 23 SEM image of TSOP component with SnCu surface finish showing tin whiskers on lead face

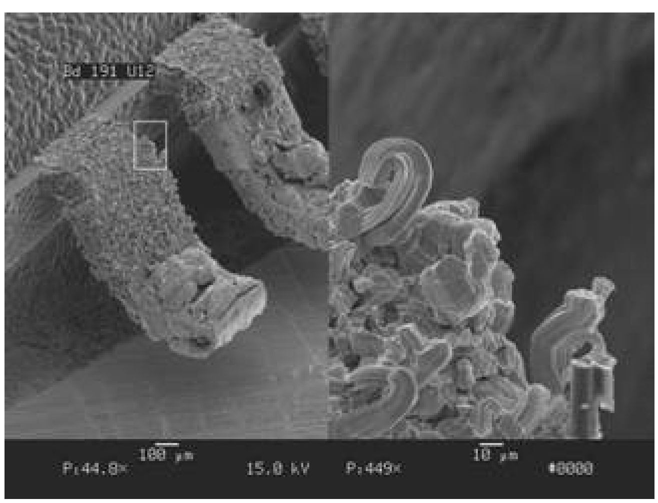


Figure 24 SEM image of TSOP component with SnCu surface finish showing tin whiskers on upper knee edge of lead

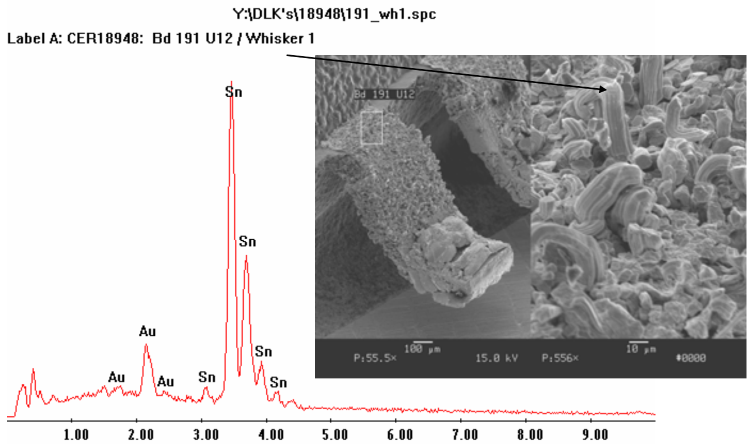


Figure 25 SEM EDX scan of a single tin whisker, TSOP-50 with SnCu surface finish, showing chemical composition.

Only a handful of whiskers were observed on the TQFP-144 components for all of the test vehicles. However, the whiskers observed were of significant interest. Figure 26 thru Figure 28 illustrate a TQFP-144 component, with a matte tin surface finish, on a legacy ("Rework") test vehicle that was soldered with SnPb solder. Small lead (Pb) whiskers were found on the upper knee of the component lead. The Pb whisker phenomena were also observed sporadically on the TSOP-50 components with SnPb surface finish (Figure 29 thru Figure 31). The Pb whiskers observed in this investigation were significantly larger than whiskers found on SnPb finishes documented in other industry investigations [9].

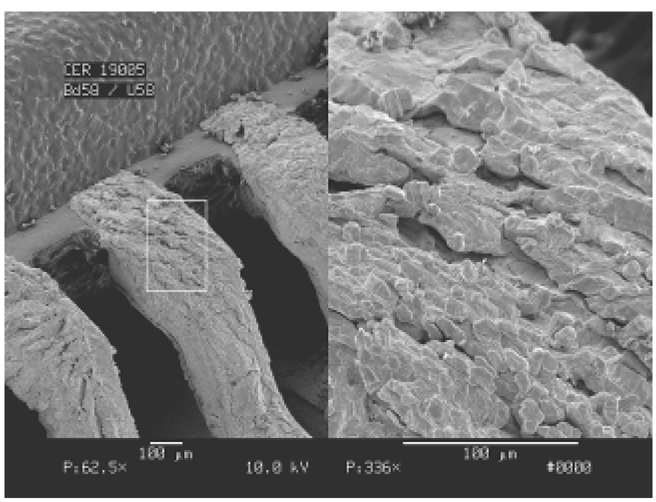


Figure 26 SEM image of whiskers, TQFP component with matte tin surface finish

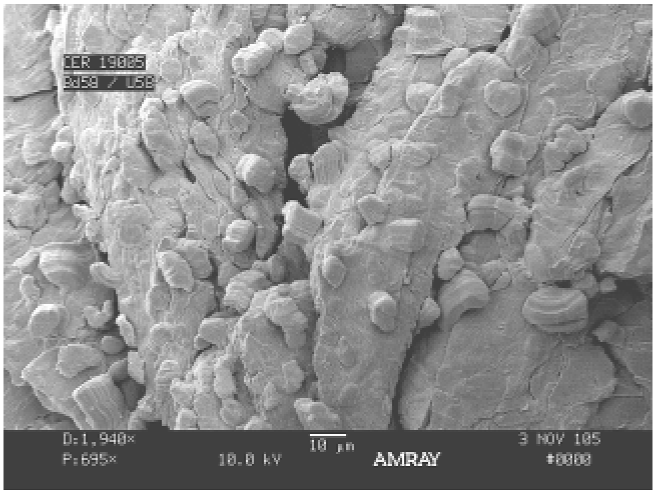


Figure 27 Magnified SEM image of whiskers, TQFP component with matte tin surface finish

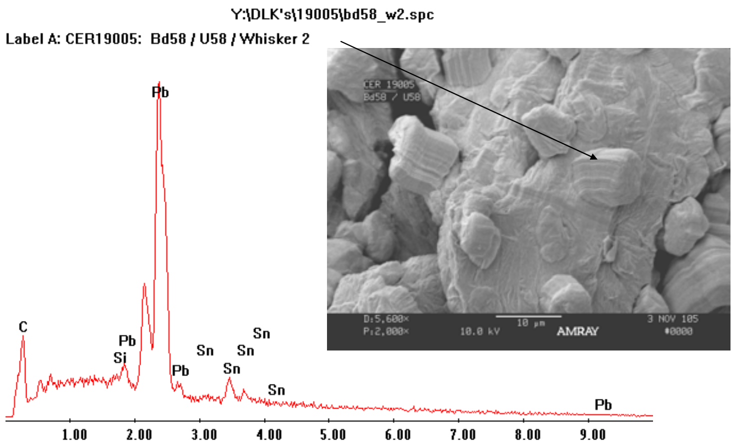


Figure 28 SEM EDX scan of an individual whisker, TQFP component with matte tin surface finish, showing Pb chemical composition

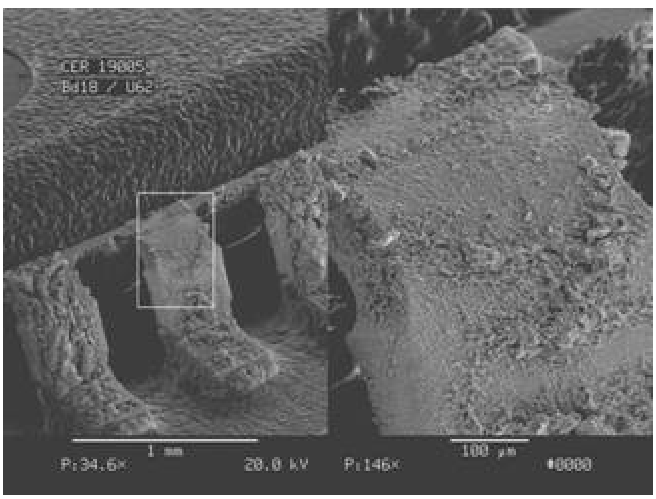


Figure 29 SEM image of TSOP component with SnPb surface finish showing whiskers on upper knee of lead

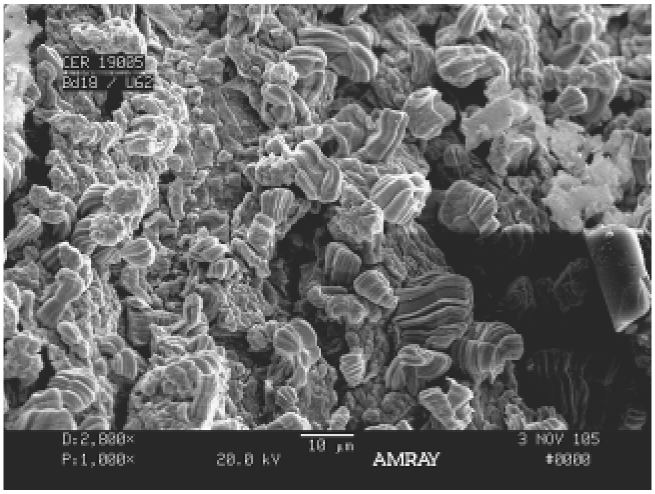


Figure 30 SEM image of TSOP component with SnPb surface finish showing whiskers on upper knee of lead

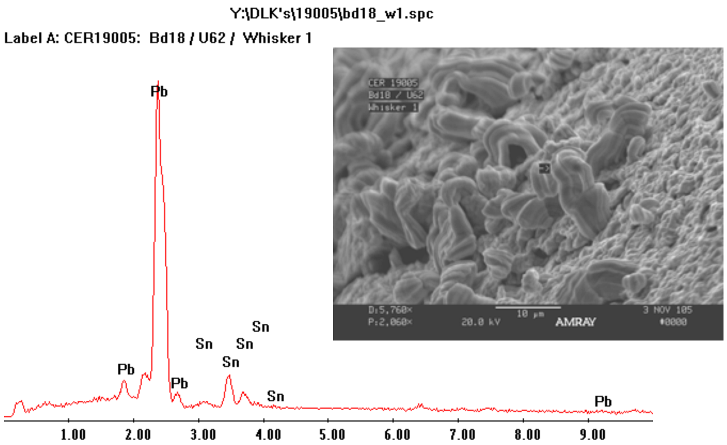


Figure 31 SEM EDX scan of an individual whisker, TSOP component with SnPb surface finish showing Pb chemical composition

No whiskers (either Sn or Pb) were observed for the PLCC-20 or DIP-20 components. Table 4 lists the summary of the whisker observations for the -55ºC to +125ºC thermal cycle test vehicles.

Component Type	Component Finish	Whisker Observations	Typical Whisker Diameter	Typical Whisker Length	Maximum Length Observed
TSOP	SnPb	Significant Whiskering Observed	8 µm	5 - 20 µm	50 µm
	SnCu	Significant Whiskering Observed	8 µm	10 - 30 µm	120 µm
DIP	Sn	No Whiskers Observed	NA	NA	NA
PLCC	Sn	No Whiskers Observed	NA	NA	NA
TQFP	Sn	Sporatic Whiskering Observed	8 µm	8 - 12 µm	12 µm
Note: Whiskers observed with severely twisted/contorted shapes or with stubby shapes					

Table 4 Whisker Observation Summary

Failure Analysis – Interaction of Bismuth (Bi) and Lead (Pb)

The interaction of Pb and Bi in a Pbfree soldering system has been a topic of extensive debate and discussion. The 58Bi42Sn solder alloy has a eutectic melting point of 138°C and has been extensively used in industry soldering applications for a number of years. The introduction of Pb to a Sn/Bi solder alloy can produce the formation of a 16Sn32Pb52Bi ternary eutectic phase with a melting point of 96°C [10]. Handwerker documented, using several SnBiPb alloy compositions, that the visible formation of the 96°C eutectic ternary in the solder joint microstructure decreased significantly for a microstructure containing 6% Pb contamination [11]. Snugovsky concluded, using both Differential Scanning Calorimetry (DSC) and visual microstructual analysis, that a SnPb solder alloy could contain up to 6% Bi additions without causing the formation of the low melting eutectic ternary phase [10]. A review of this investigation thermal cycle data set shows a significant impact of having a small amount of Pb contamination in the SACB solder joints. Figure 32 shows the TSOP-50 data for the SACB solder alloy for the SnCu and SnPb component finishes. The SnPb finished TSOP-50 component solder joint integrity is clearly significantly lower. These test results does not agree with SACB solder alloy test data documented by Hwang [12] and the 0°C-100°C thermal cycle test data reported by Snugovsky [10]. The TSOP-50 Weibull data is in agreement with thermal cycle test results using SnBi finished components in SnPb solderpaste reported by Honeywell [13] and with mechanical pull test results using SnPb finished components in SnAgCuBi solderpaste reported by Kariya [14].

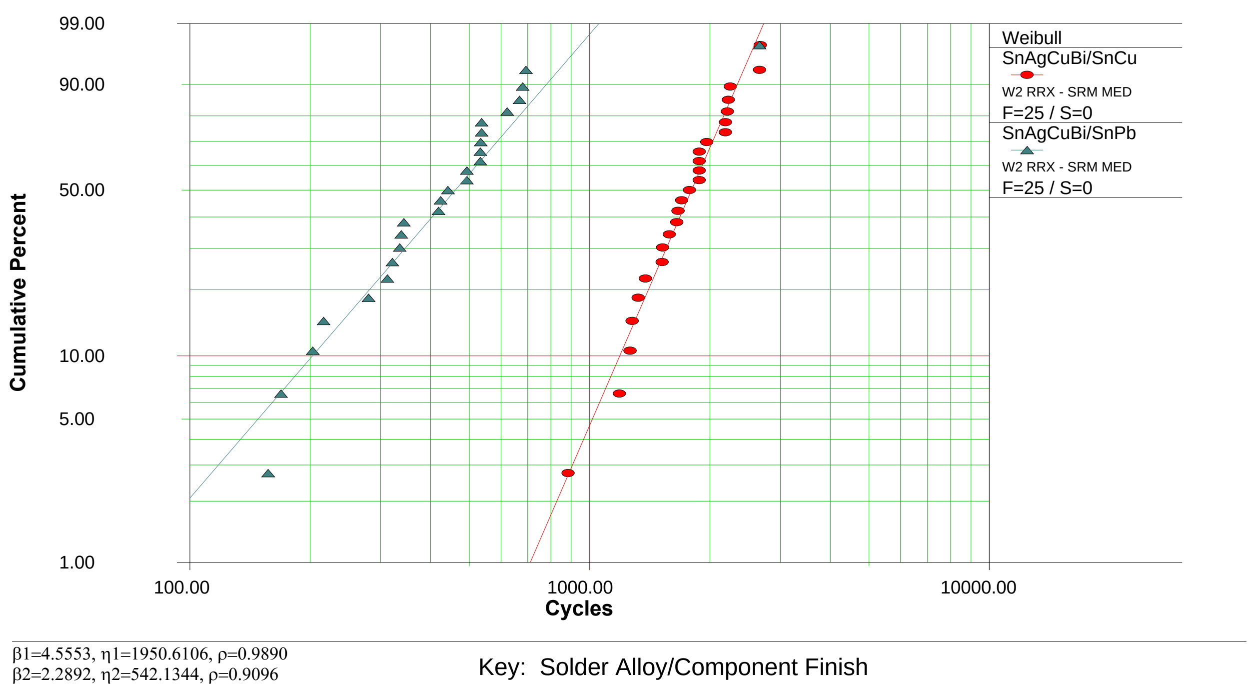


Figure 32 TSOP-50 SACB test results for the "Manufactured" test vehicles (170°C Tg)

Optical microscopy and scanning electron microscopy (SEM) inspection of a sample of the failed TSOP-50 SACB-SnPb solder joint combination was conducted. No evidence of a SnBiPb microstructual phase was observed. SEM elemental mapping was conducted on a sample of the failed TSOP-50 SACB-SnPb solder joints. Figure 33 illustrates the typical results for the mapping. No segregated SnBiPb microstructual phase regions were found. Some small segregated regions of Pb were observed in the solder joints.

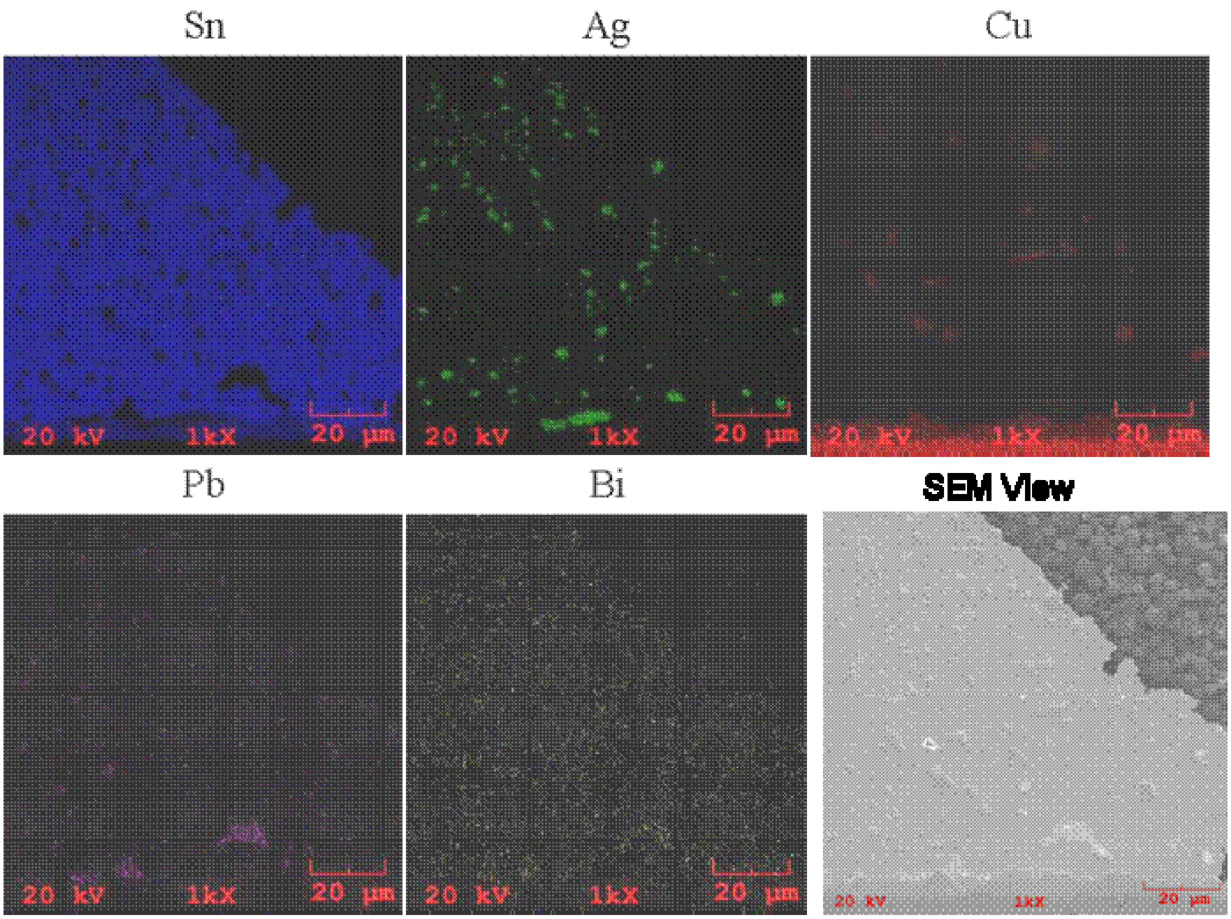


Figure 33 SEM elemental mapping results for SACB-SnPb solder joint after 4743 thermal cycles

DSC analysis was conducted to determine if the melting point of the “Manufactured” solder joints would yield a clue on the degraded solder joint integrity of the TSOP-50 SACB-SnPb combination. Several TSOP-50 SACB-SnPb and TSOP-50 SACB-SnCu solder joints were carefully removed from test vehicles. Table 5 lists the DSC results. The DSC test results illustrate the impact that the Pb contamination has on the melting behavior of the SACB solder joint.

Solder Alloy/Component Finish	DSC Data
SACB/SnPb	196.9°C
SACB/SnCu	210.0°C
SACB Melting Range	205°C-214°C
DSC settings: 10°C/min ramps, 25°C to 300°C range	

Table 5 TSOP-50 SACB/Component Finish DSC Data

The authors have hypothesized two potential root causes responsible for the Pb contamination impact on the TSOP-50 SACB solder joint integrity based on the completed failure analysis results:

1. The Pb contamination is impacting the SACB solder joint integrity by the formation of non-equilibrium SnPbBi microstructure phases. The Pb contamination is not great enough to form the microstructure phases associated with the 58Bi42Sn solder alloy (138C), the 16Sn32Pb52Bi ternary eutectic phase (96C) or the 62.5Sn/36.1Pb/1.4Ag ternary eutectic alloy (177ºC) [15]. However, Whitney and Corbin [16] have reported that ternary reactions are very sensitive to small Pb additions for SnBi solder alloys. The formation of non-equilibrium ternary phases can cause broad melting effects on the melting behavior on solder alloy solidification. The DSC data of this investigation shows a nondescript impact rather than a specific ternary reaction in a similar manner.

2. The DSC test results may be an indication of the Sn63Pb37 eutectic alloy development at the solder joint grain boundaries. The development of the Sn63Pb37 alloy at the grain boundaries would impact the thermal cycle solder joint integrity. The SEM elemental mapping did show some evidence of segregated Pb regions in the SACB solder joint thus the existence of the eutectic alloy at the grain boundaries would be possible. Table 6 illustrates the impact of TSOP Pb contamination of a SnAgBi solder alloy reported by ATT/Sandia National Laboratory [17]. The thermal cycle conditioning parameters were 0°C to 100°C, 15 minute dwells and 20°C/minute ramps. The pull test cross head speed was 9 mm/minute. The pull strength of the Pb contaminated solder joints was degraded in comparison to the non-contaminated case.

Thermal Cycles	SnAgBi	
	SnPb/OSP	Sn/OSP
0	2.75 +/- 0.61	5.31 +/- 0.67
10,106	3.13 +/- 1.24	5.34 +/- 0.74

Table 6 Impact on pull strength values of Pb contamination of SnAgBi TSOP solder joints

Failure Analysis – Mixed BGA Metallurgies

The issue of mixing Pbfree component finishes with SnPb soldering processes is another topic of extensive discussion. A portion of the “is mixing Pbfree and SnPb an issue?” discussion is due to misinformation. Typical SnPb soldering processes do not exceed a component lead or termination temperature of 225°C, therefore a metallurgical connection is achieved due to diffusion rather than dissolution phenomena for Pbfree component finishes such as Sn or NiPdAu. The thickness of Pbfree finishes on plated thru hole or surface mount components is relatively thin and therefore comprises only a small portion of the overall final solder joint. However, the solderball of an area array component such as the BGA-225 used in this investigation contributes the majority volume of the final solder joint. If the BGA solderball is a Pbfree solder alloy (the BGA-225 components for this investigation used a SAC solder alloy) the soldering process must either achieve dissolution (e.g. melting) of the solderball or allow uniform diffusion of the solderpaste into the solderball. A number of industry investigations [18, 19] have demonstrated that achieving a uniform BGA solder joint microstructure is a key parameter in having reliable solder joint integrity. STMicroelectronics conducted an investigation on the BGA mixed metallurgy issue and demonstrated that solder joint integrity is acceptable provided a uniform solder joint microstructure is created (Figure 34) [20]. Figure 35 shows a BGA-225 SnPb-SnPb (e.g. solderpaste/component finish) combination which is typical of a matched SnPb solder combination. This solder joint had a uniform original microstructure and failed after completing 533 total thermal cycles.

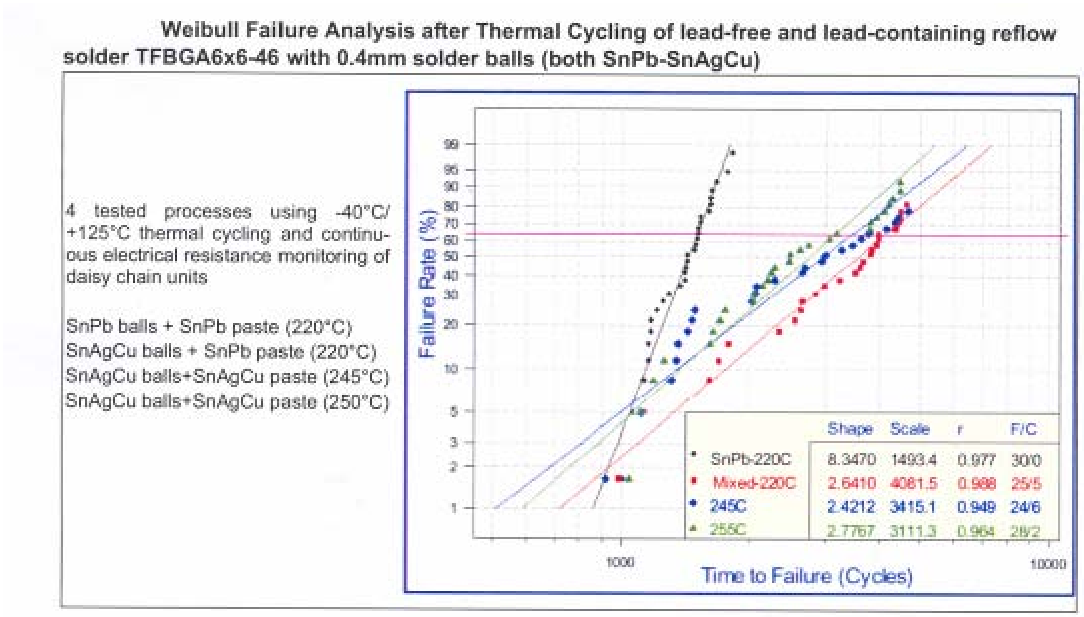


Figure 34 Mixed BGA metallurgy test results from STMicroelectronics reference [20]

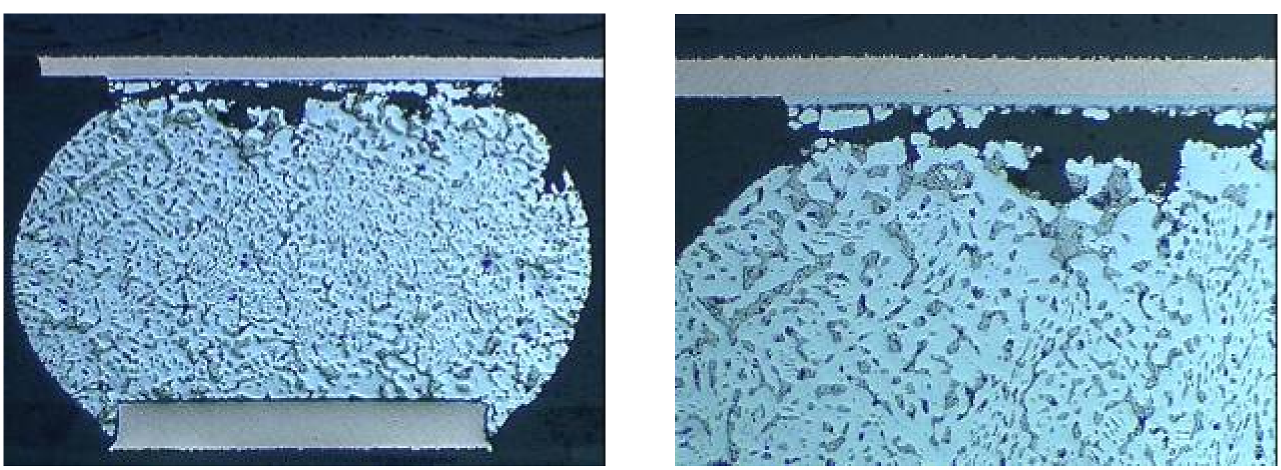


Figure 35 (left) BGA-225 SnPb-SnPb solder joint; (right) magnified view of solder joint crack path (test vehicle 58)

Figure 36 shows a BGA-225 SAC-SAC combination which is typical of a matched SAC solder combination. This solder joint had a uniform original microstructure and failed after completing 3011 total thermal cycles.

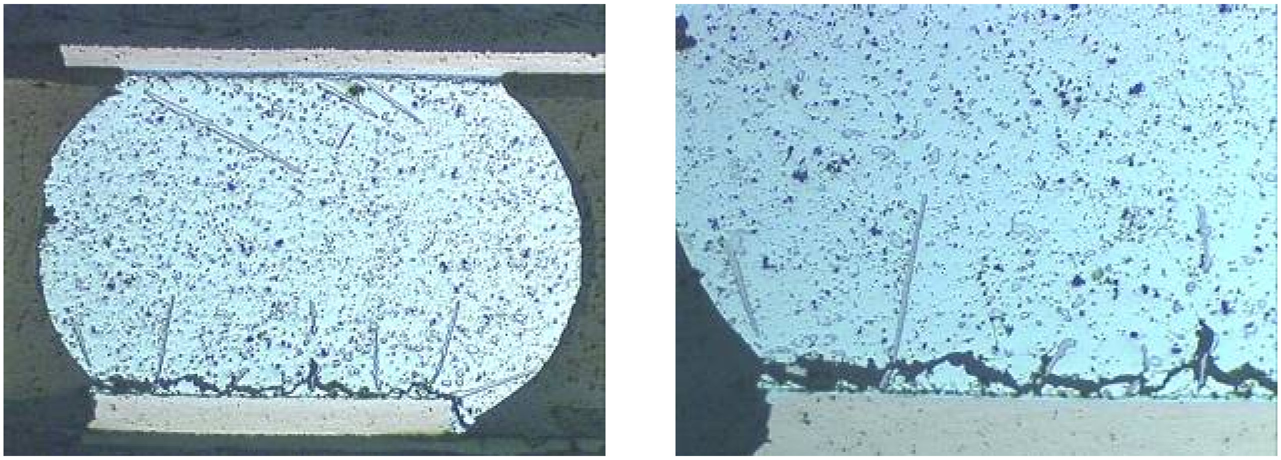


Figure 36 (left) BGA-225 SAC-SAC solder joint; (right) magnified view of solder joint crack path (test vehicle 86)

Figure 37 illustrates that the non-eutectic solidification behavior of the SAC solder alloy can produce some non-uniform solder joint shapes that have good thermal cycle reliability – the solder joint had not failed after 4743 total thermal cycles.

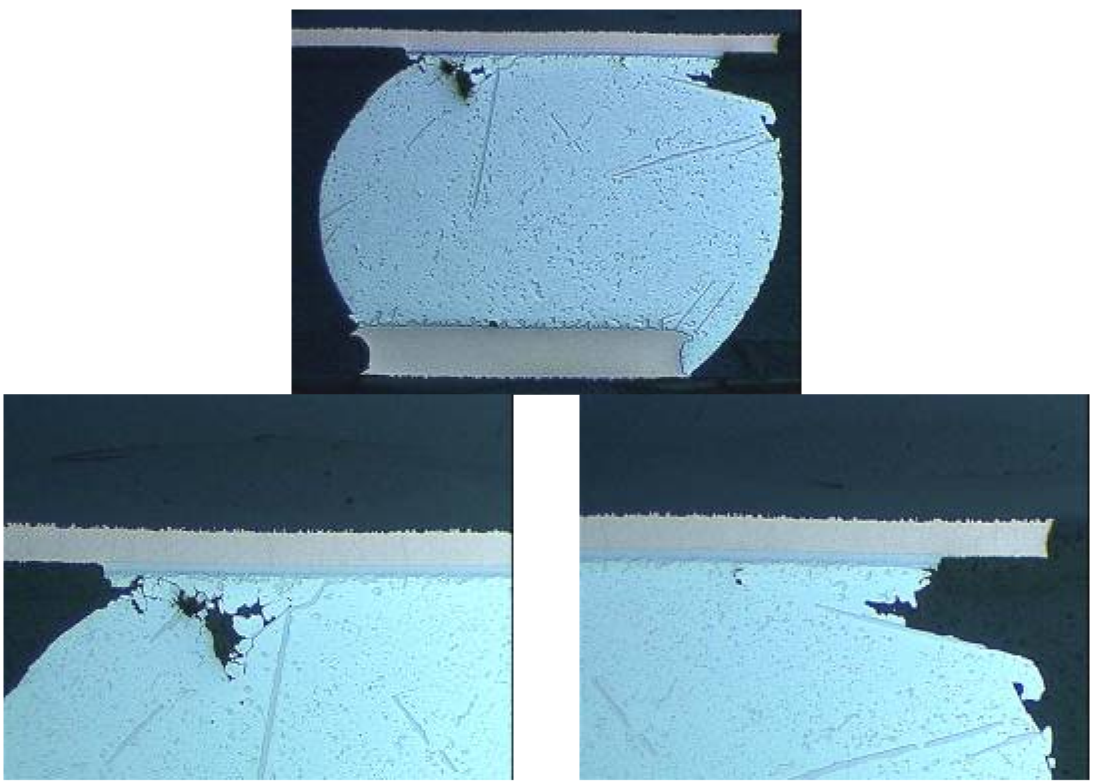
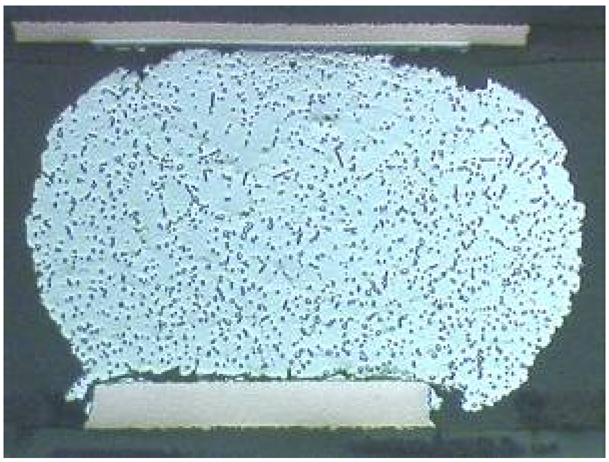


Figure 37 (top) BGA-225 SAC-SAC solder joint; (left, right) magnified view of solder joint (test vehicle 85)

The legacy ("Rework") test vehicles did contain a number of rework BGA-225 component combinations that demonstrate that a non-uniform solder joint microstructure will result in degraded solder joint thermal cycle integrity. Figure 38 shows a BGA-225 SnPb-SnPb combination that was reworked with a BGA-225 SAC component. This solder joint had a non-uniform original microstructure and failed after completing 822 total thermal cycles. Examination of the solder joint crack path revealed that some of the original SnPb remained on the test vehicle pad after the original BGA-225 SnPb component was removed despite extensive rework procedures to avoid any Pb contamination.



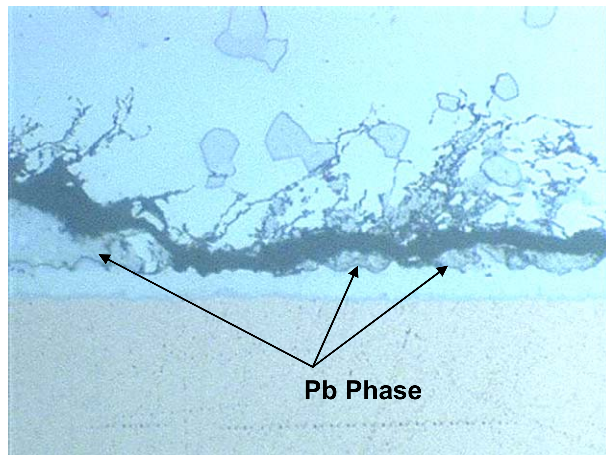
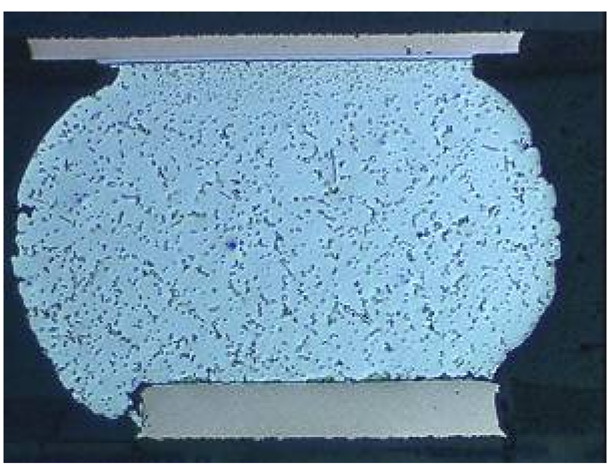


Figure 38 (left) BGA-225 SAC-SAC solder joint; (right) magnified view of crack with Pb phase present

The present of Pb at the solder joint – test vehicle pad interface resulted in the reduced solder joint thermal cycle integrity. Figure 39 shows a similar case of Pb contamination for a BGA-225 SnPb-SnPb combination that was reworked with a BGA-225 SAC component on test vehicle 167.



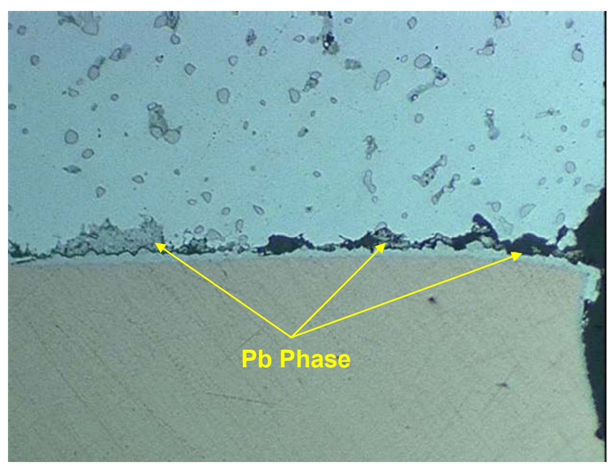


Figure 39 (left) BGA-225 SAC-SAC solder joint; (right) magnified view of crack with Pb phase present

The Pb contamination of a BGA-225 SAC solder joints was also found during the failure analysis of several test vehicles in which SAC solderpaste was used with a BGA-225 SnPb finish. A review of the test vehicle assembly reflow profiles shows that the achieved reflow temperatures should have resulted in the SnPb solderball undergoing complete dissolution. However, the metallographic cross-sections show that some Pb phase present in the crack paths, causing solder joint degradation (Figure 40 and Figure 41: test vehicle 88). The authors believe that Pb contamination is a case of metallurgical incompatibility that can be minimized but not eliminated through enhanced process control. High performance applications may determine that the risk associated with this phenomenon is too high for their products.

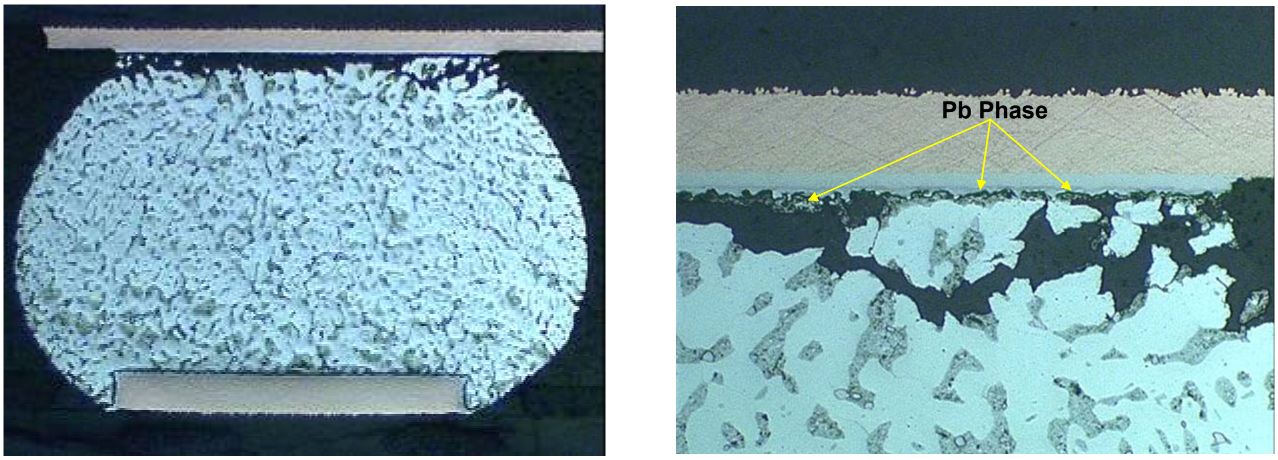


Figure 40 (left) BGA-225 SAC-SnPb combination solder joint; (right) magnified view of crack with Pb phase present

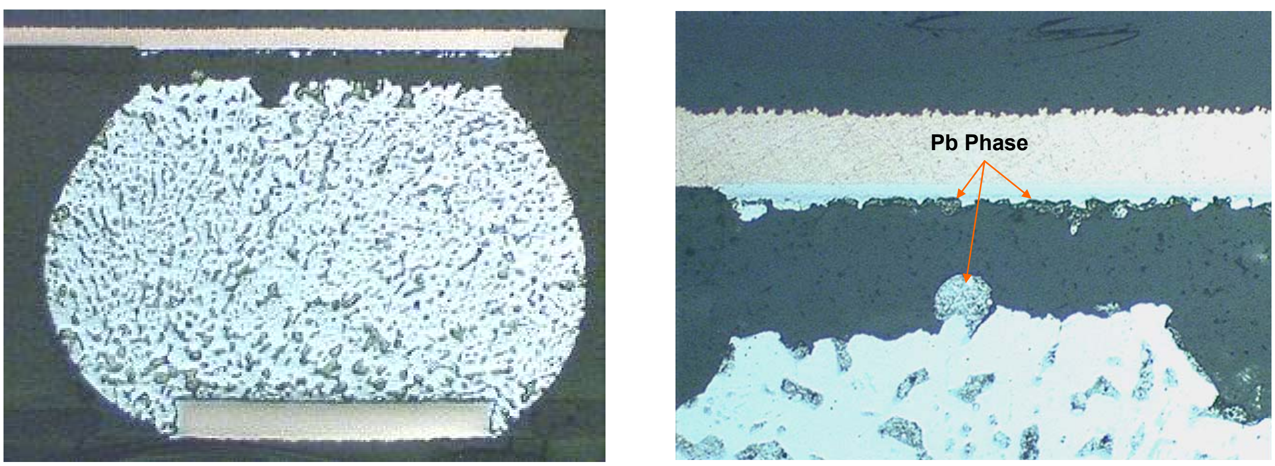


Figure 41 (left) BGA-225 SAC-SnPb combination solder joint; (right) magnified view of crack with Pb phase present

Failure Analysis – Solder Joint/Intermetallic Interface Voiding

There has been serious interest by the electronics industry concerning the development of voids in surface mount solder joints in conjunction with the introduction of Pbfree soldering processes. Borgesen reported the weakening of a printed wiring board pad structure due to the formation of "microvoids" in the intermetallic phases for a SAC solder alloy [21] in 2004. The formation of microvoids had been shown by Vianco to be a Kirkendall void effect associated with the formation of the Cu_3Sn intermetallic due to the diffusion imbalances of copper and tin diffusion rates [22]. The Kirkendall voids shown in Figure 42 were formed after aging the sample at 205°C for 300 days.

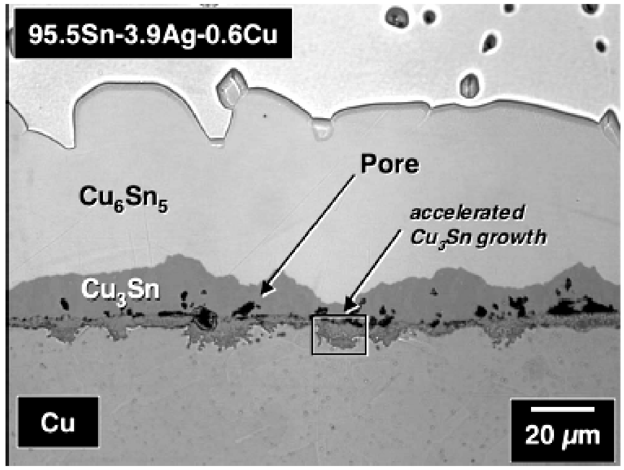


Figure 42 Formation of Kirkendall Voids due to copper and tin diffusion imbalances from Vianco reference [22]

The thermal cycle testing was halted after 4743 thermal cycles. The amount of accumulated solder joint aging time at 125°C for this number of cycles, based on the 30 minute dwell time, was approximately 2372 hours. Failure analysis was conducted on a number of BGA-225 components to determine if Kirkendall voiding was present. Additional metallographic cross-sectioning precautions were followed to avoid smearing over possible voids or to artificially introduce voids. The cross-sections were examined in both etched and unetched conditions. Figure 43 shows the typical solder joint/intermetallic interface observed after 2372 hours. No Kirkendall voiding phenomena was observed during the optical examination of the cross-sections. SEM examination of a number of samples was conducted to determine if Kirkendall voiding was present. Figure 44 shows the typical solder joint/intermetallic interface observed during the SEM examination after 2372 hours. No Kirkendall voiding phenomena was observed. The BGA-225 solder joint/intermetallic interfaces produced in this study are more representative of real world electronic product thermal excursions than the high temperature static baking conditioning that has produced a number of the Kirkendall voiding reports. If a SAC solder alloy is more prone to Kirkendall void formation, the more relevant concern would be "what is the time duration in real world thermal excursion terms that produces Kirkendall voiding solder joint integrity risk?". The authors believe that the results of this investigation show that some of the industry Kirkendall voiding phenomena concerns may be overstated.

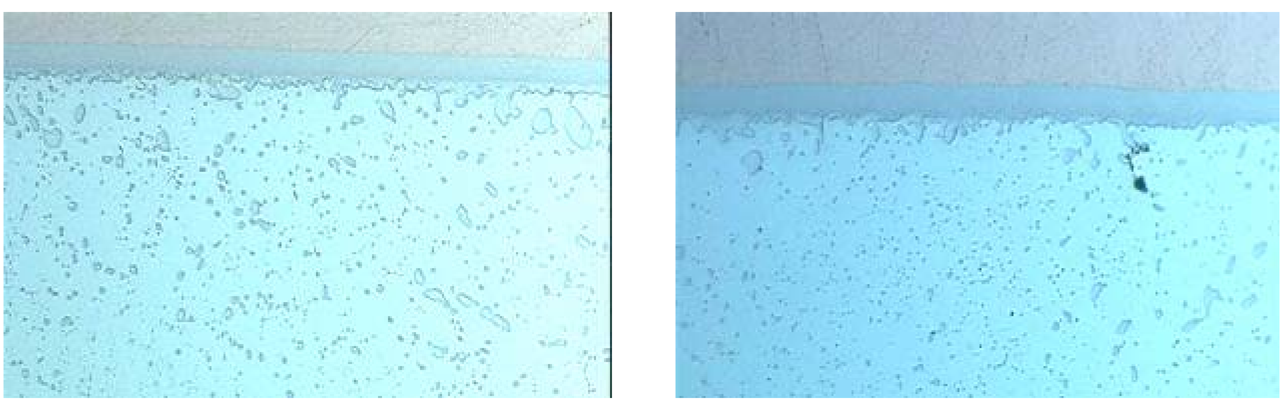


Figure 43 (left/right) BGA-225 SAC-SAC combination cross-section of solder joint/intermetallic interface

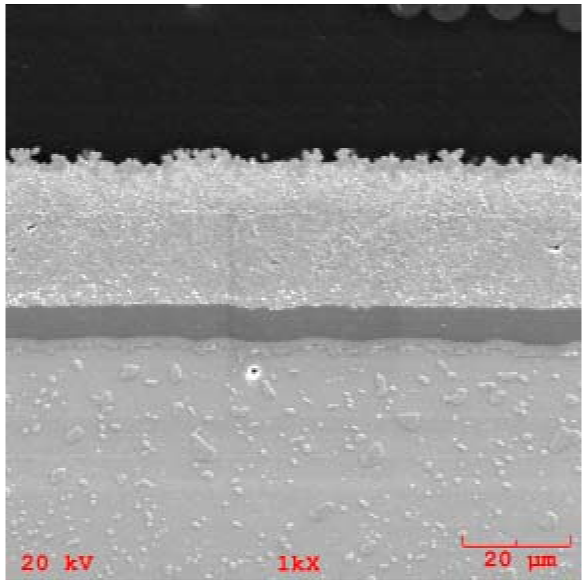


Figure 44 BGA-225 SAC-SnPb combination SEM view of solder joint/intermetallic interface

Failure Analysis – Solder Joint Shrinkage Voids and Solder Joint Fillet Lifting

The BGA-225 solder joints were specifically examined for the presence of shrinkage voids. Shrinkage voids are phenomena observed in high tin containing Pbfree solder alloys and are the result of the formation of a tin dendritic matrix. The shrinkage voids are not associated with Kirkendall voiding phenomena, but instead are caused by the solidification behavior of the Pbfree solder alloy. Eutectic SnPb solder alloys do not experience shrinkage voiding. The purpose of the examination was to determine if any thermal cycle cracking and/or solder joint failures could be attributed to the presence of shrinkage voids. Figure 45 illustrates the shrink voids observed during the examination. Thermal cycle cracking or solder joint failures were not found to be associated with the shrinkage voids observed. Other industry investigations [18] have documented similar results for the shrinkage voids.

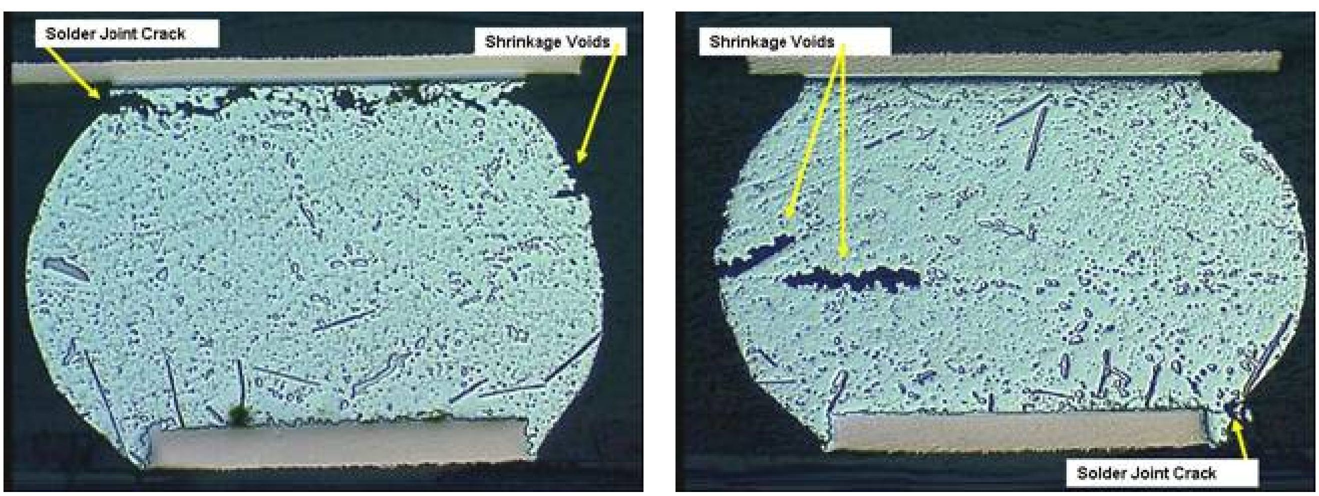


Figure 45 (left) SAC-SAC "Manufactured" solder joint Small shrinkage voids: (right) Large shrinkage voids

A second phenomena resulting from the solidification behavior of the Pbfree solder alloys is fillet lifting. Fillet lifting is primarily associated with plated thru hole technology and the wave soldering process. The DIP-20 components on the test vehicles that were processed using the SAC and SNIC solder alloys were examined for the presence of fillet lifting and shrinkage voids. Using Rockwell Collins standard solder joint inspection magnification values no instances of either fillet lifting or shrinkage voids were found. However, during the failure analysis of the DIP-20 component some occurrences of both phenomena were observed. Figure 46 illustrates a fillet lift found on a DIP-20 SAC-NiPdAu combination. Despite the fillet lift and visible cracking, this solder joint did not fail after 4743 total thermal cycles. Figure 47 illustrates a shrinkage void found during the failure analysis. These shrinkage voids did not contribute to the failure of the solder joint – after 4743 total thermal cycles the solder joint had not failed. Both the shrinkage void and fillet lifting observations of this investigation are in agreement with other industry reports [23].

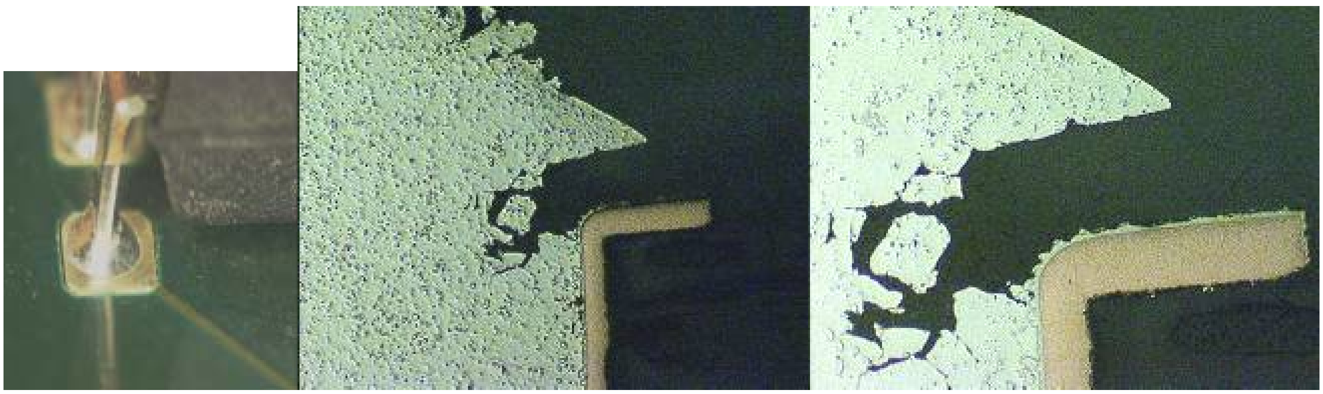


Figure 46 DIP-20 SAC-NiPdAu combination illustrating a fillet lift (no solder joint failure after 4743 thermal cycles)

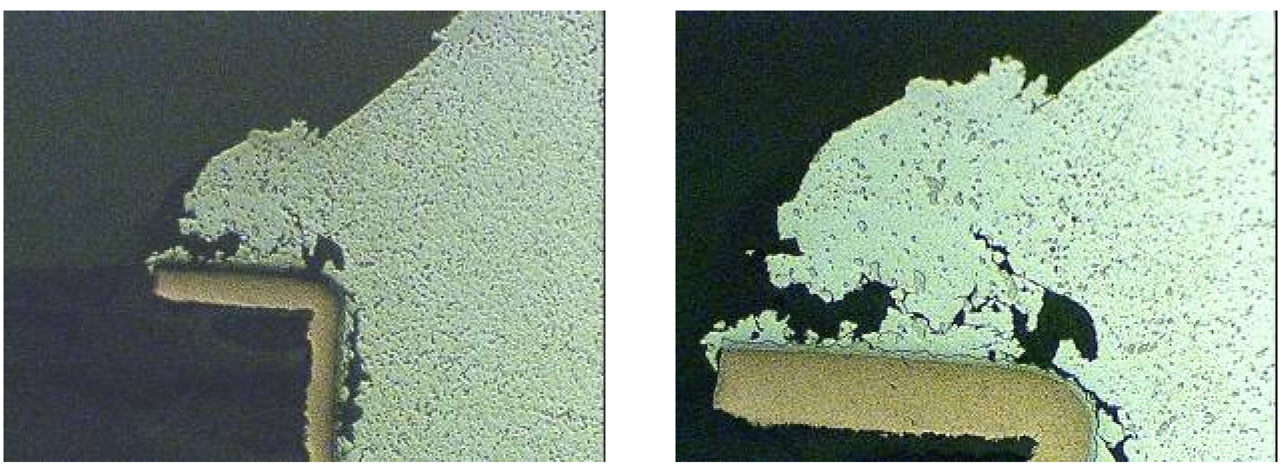


Figure 47 DIP-20 SAC-NiPdAu combination with a shrinkage void (no solder joint failure after 4743 thermal cycles)

Failure Analysis – PWB Pad Dissolution

A number of metals undergo substantial dissolution when exposed to molten tin. Sharif and Chan reported that the SAC solder alloy dissolution rate of BGA copper pads was much more time/temperature sensitive than using the traditional SnPb solder alloy [24]. The bottom side test vehicle copper pad thicknesses were measured as part of the overall DIP-20 component failure analysis to determine if the wave soldering process for each of the solder alloys resulted in significant copper pad dissolution. Table 7 shows the measurements results and Figure 48 shows the appearance of the copper pads after wave solder processing. The loss/gain measurement values are not statistically significant for the thermal cycle test vehicle pads. Copper pad erosion may be a concern for other Pbfree solder alloys, or possibly a different set of wave solder process parameters than those used in this investigation. The specific copper plating chemistry characteristics may also play an important role in the copper dissolution rates. Further investigation of copper pad dissolution is recommended.

Solder Alloy	Pre Wave Pad Thickness	Post Wave Pad Thickness	Pre/Post Pad Thickness Delta
SnPb	0.00217 inches	0.00178 inches	loss of 0.0004 inches
SAC	0.00226 inches	0.00226 inches	0.0000 inches
SNIC	0.00208 inches	0.00222 inches	gain of 0.0001 inches

Table 7 DIP-20 Copper Pad Thickness Measurements

Figure 48 DIP-20 copper pads; (left) SAC alloy; (center) SNIC alloy; (right) SnPb alloy

Failure Analysis – TQFP Wetting Issues

One of the most confounding thermal cycle test results revealed by the statistical analysis was the high failure rate of the TQFP-208 component U3. TQFP-208 components U3 and U57 were selected as part of the rework segment of the investigation. Components U3 and U57 were identical, were reworked by the same operator, and utilized the same rework procedure. The only difference between the two components was their physical location of the test vehicle. There should have been little or no difference in the failure rate of the two TQFP-208 components. However, U3 had an N10 value of 41cycles and U57 had an N10 value of 1905 cycles for the SACB solder alloy – a dramatic difference. The JG-PP consortia team did an extensive review of the U3/U57 rework process and found an unexpected root cause. The U3 TQFP-208 was the last component of four components reworked in a cluster but U57 was the only component reworked in its location on the test vehicle. The specific rework order for the four component cluster containing U3 oxidized the test vehicle pads, resulting in a weaker solder joint. Figure 49 illustrates the pad wettability differences found for components U3 and U57 during the failure analysis optical examination after 4743 thermal cycles. Figure 50 illustrates the pad wettability difference found for components U3 and U57 during the cross-sectional analysis prior to thermal cycle testing.

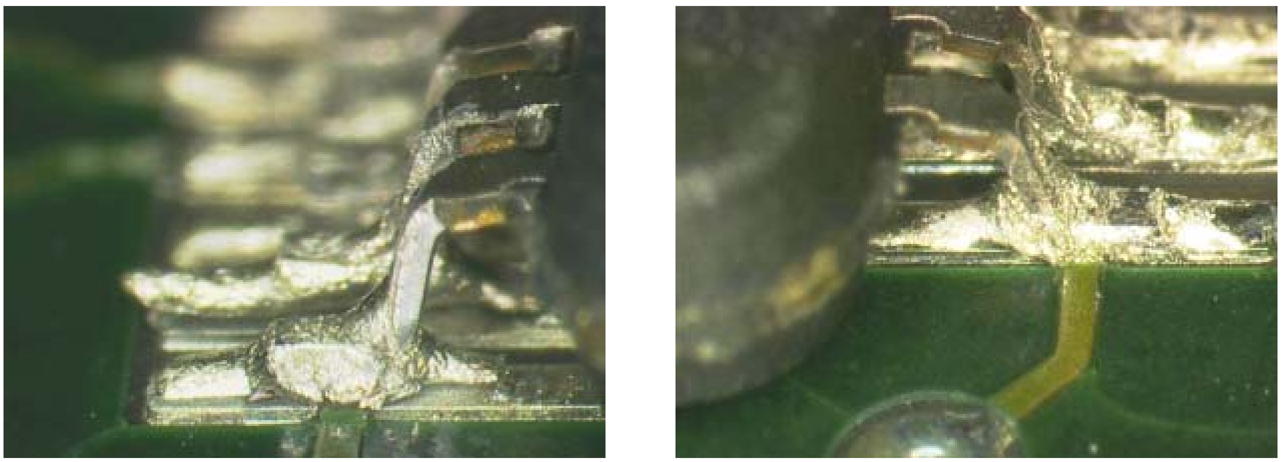


Figure 49 TQFP-208 SACB U3 (left) versus U57 (right) optical wettability comparison

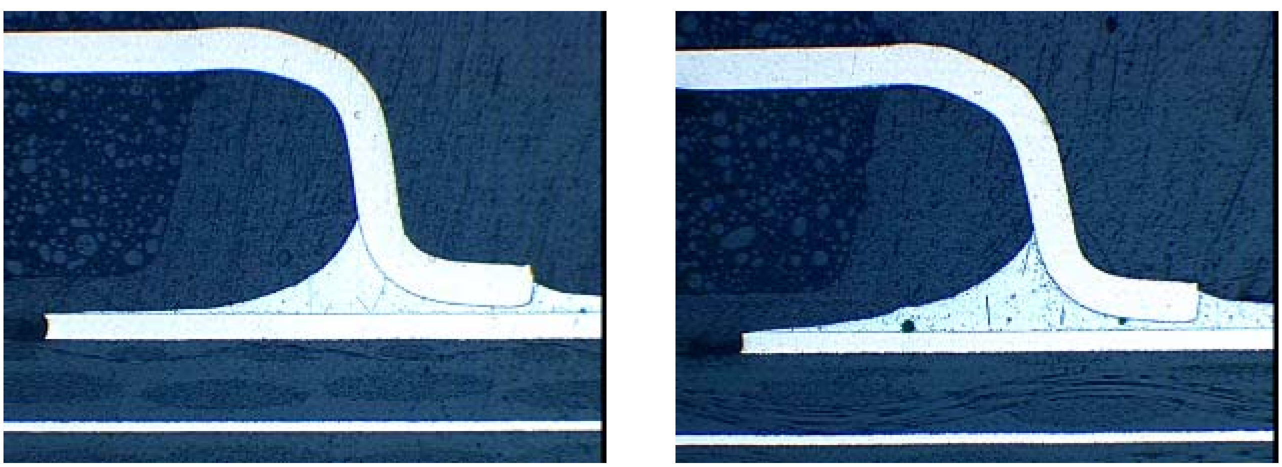


Figure 50 TQFP-208 SAC U3 (left) versus U57 (right) cross-sectional wettability comparison

Failure Analysis – Plated Thru Hole Integrity

The impact of Pbfree soldering processes on printed wiring board structures is a significant concern for the electronics industry [25]. Plated thru hole integrity was not included in this investigation as a primary test structure. However, one plated thru hole was included on each test vehicle due to the availability of an unused event detection system channel. As discussed in the statistical analysis section, only two plated thru holes of the population of 30 total plated thru holes registered as electrical failures – one failing at 1779 thermal cycles and one failing at 2568 thermal cycles. Figure 51 illustrates the cracked plated thru hole on a SAC "Manufactured" test vehicle. Plated thru hole wall cracks were found at the center of the plated thru hole structure. The overall failure result trend is encouraging but the small sample size for the various configurations tested is not a statistically sufficient population for deriving conclusions. It is anticipated that the increased soldering process temperatures associated with Pbfree soldering should result in a decrease in plated thru hole integrity. Additional testing on printed wiring board structures, e.g. plated thru holes, vias, signal traces, should be conducted.

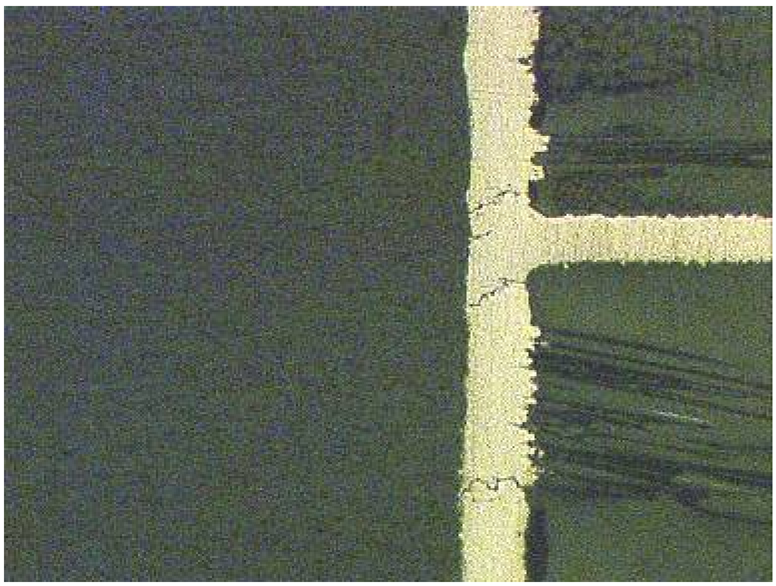


Figure 51 Metallographic cross-sectional view of plated thru hole wall cracks

100X Magnification (Component U64, test vehicle 126)

Conclusions

The investigation conclusions were:

- BGA-225 components: the Pbfree solder alloys had equal to or better thermal cycle performance than the SnPb solder alloy baseline for the matched solder alloy/component finish combinations. Mixed metallurgy solder alloy/component finish combinations such as SAC-SnPb or SACB-SnPb had degraded thermal cycle solder joint integrity in comparison to the SnPb solder alloy baseline solder joint integrity.

- CLCC-20 components: the Pbfree solder alloys had lower solder joint thermal cycle performance in comparison to the SnPb solder alloy baseline except for the SACB-SACB solder alloy/component finish combination. The ceramic construction of the CLCC-20 component induced a higher CTE mismatch resulting in a high solder joint stress that impacted the Pbfree solder alloys to a greater extent than the SnPb solder alloy baseline.

- TQFP-144 components: the SACB solder alloy had better performance than the SnPb solder alloy baseline. The SAC solder alloy had a mixed performance results in comparison to the SnPb solder alloy baseline.

- TQFP-208 components: the Pbfree solder alloys had equal to or better than thermal cycle performance in comparison to the SnPb solder alloy baseline solder joint integrity.

- TSOP-50 components: the SAC solder alloy had lower performance in comparison to the SnPb solder alloy thermal cycle solder joint integrity. The SACB solder alloy had greater performance in comparison to the SnPb solder alloy thermal cycle solder joint integrity except for the SnPb component finish cases. The SnPb component finish created a Pb contamination issue resulting in degraded solder joint integrity.

- Rework practices: the rework aspects of the investigation produced mixed results with some cases of the Pbfree solder alloys having better performance or worse performance than the SnPb solder alloy baseline solder joint integrity.

- Tin Whiskers: occurrences of both Sn and Pb whiskers were found on the thermal cycle test vehicles after the completion of 4743 total thermal cycles. The TSOP-50 components were the primary whisker generators. The Sn plated TQFP-144 components were observed to have sporadic tin whisker occurrence. The Sn plated DIP-20 and PLCC-20 components were not observed to have any tin whisker occurrence. None of the whiskers observed violated minimum electrical spacing dimensions.

- The SACB solder alloy thermal cycle solder joint integrity was significantly impacted by SnPb component finish combinations.

- Solder joint – intermetallic interface voiding: No Kirkendall voiding was observed at the solder joint/intermetallic interface after the accumulation of a total of 2372 hours at 125°C during the thermal cycle testing.

- Solder Joint Shrinkage Voids and Fillet Lifting: No thermal cycle failures were observed due to the presence of solder joint shrinkage voids or fillet lifting phenomena.

Recommendation

The investigation recommendation was:

- The feasibility of using Pbfree solder alloys in place of SnPb solder alloys for new product designs was demonstrated under thermal cycle test conditions. Additional investigation and characterization of Pbfree solder alloys will be required as a segment of a Pbfree solder alloy implementation plan. The application/introduction of Pbfree soldering processes for legacy product designs is not recommended without extensive materials characterization and product design review.

Acknowledgements

The authors would like to thank the Joint Council on Aging Aircraft (JCAA)/ Joint Group on Pollution Prevention (JG-PP) Pbfree Solder program and Rockwell Collins Inc. for project funding, Ken Blazek for metallographic cross-sectioning efforts, Dwayne Koch for SEM analysis, Dr. Paul Vianco of Sandia National Laboratories for DSC analysis, Jeff Bradford of Raytheon for statistical analysis assistance, and Kurt Kessel of NASA for his scathing critique of the manuscript.

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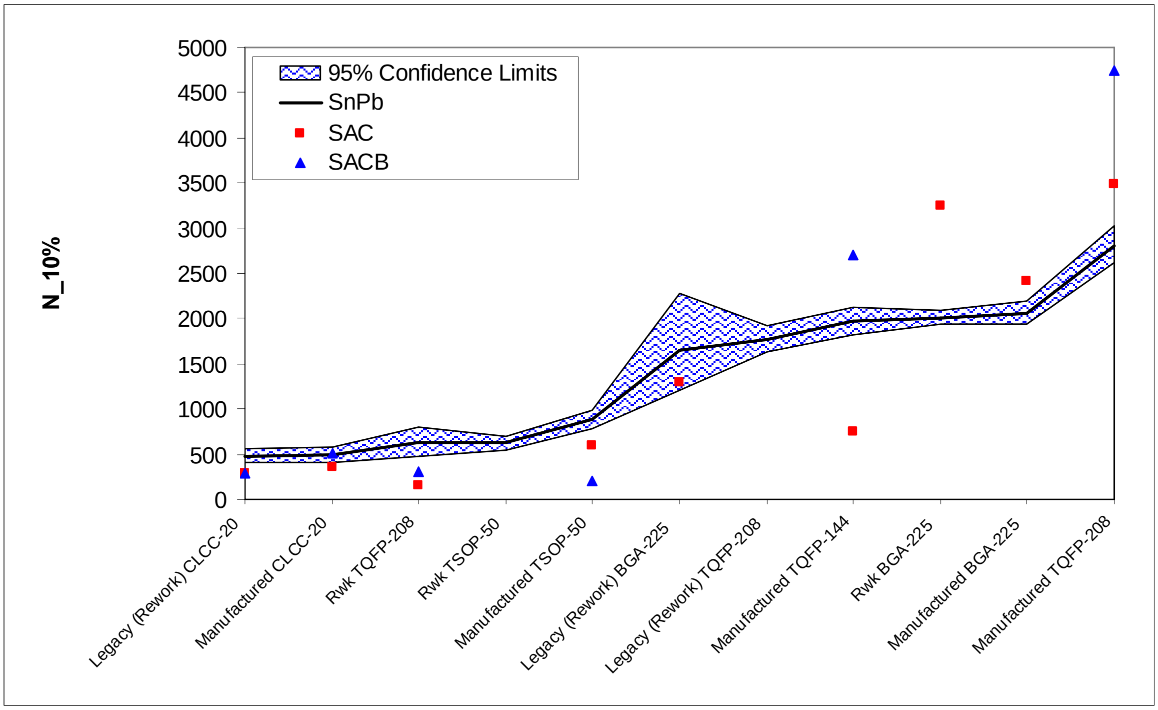
Appendices

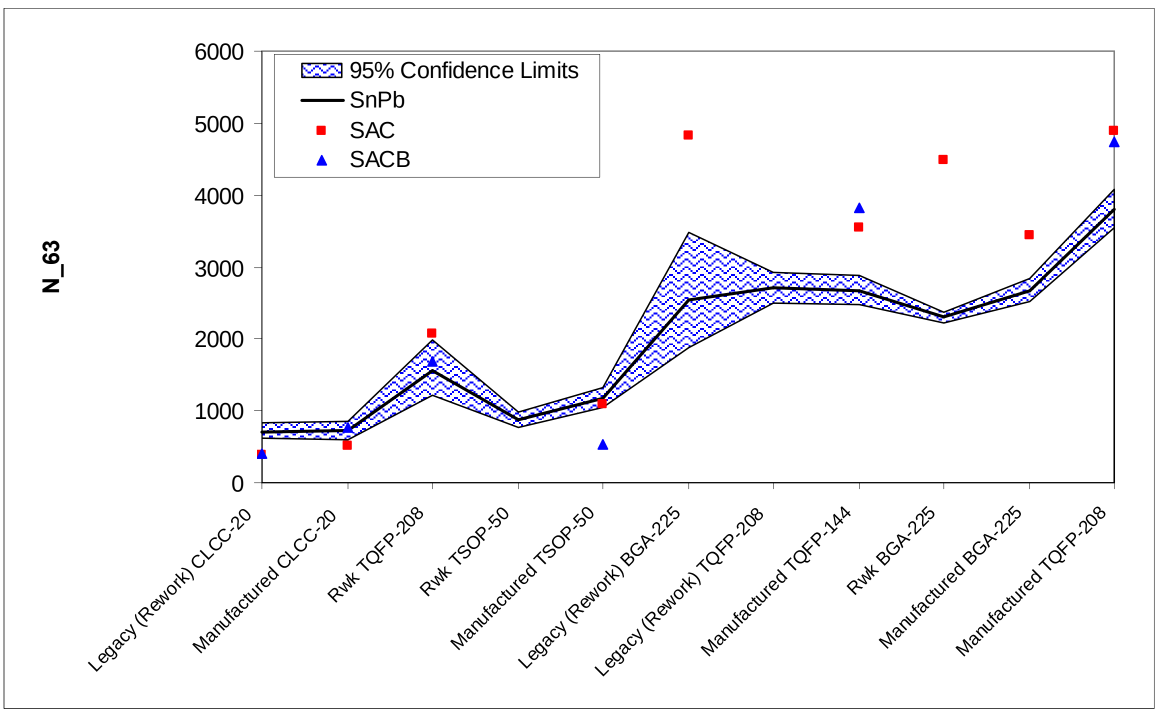
List of Figures in the Appendices

List of Figures in the Appendices

Appendix A Solder Comparison: Average Values to Control Spread



App Fig 1 Pbfree Compared to Tin-Lead Controls: 10% Failure Level in RCI Thermal Cycling



App Fig 2 Pbfree Compared to Tin-Lead Controls: 63% Failure Level in RCI Thermal Cycling

Appendix B

App Table 1 N1/N10/N63 Solder Performance for -55C to +125 C Thermal Cycle Testing

Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	1068	1822	2686
	SAC/SAC	533 (1100)	1248 (2394)	3675 (3447)
	SACB/SAC	2894	3123	4152
	SAC/SnPb	4 (229)	98 (321)	2743 (2113)
	SACB/SnPb	1536	1626	2560
CLCC-20	SnPb/SnPb	455	469	727
	SAC/SAC	288	358	510
	SACB/SACB	493	498	786
	SAC/SnPb	377	382	580
	SACB/SnPb	455	444	645
TQFP-144	SnPb/Sn	1473	1946	2681
	SAC/Sn	245	721	3626
	SACB/Sn	2605	2584	3988
TQFP-208	SnPb/ NiPdAu	1068	2138	3900
	SAC/ NiPdAu	704 (2833)	1696 (3484)	10029 (4907)
	SACB/ NiPdAu	506	*NF	*NF
TSOP-50	SnPb/SnPb	822	854	1192
	SAC/SnCu	440	634	1070
	SACB/SnCu	884	1179	1956
	SAC/SnPb	382	584	1096
	SACB/SnPb	157	173	570
Rwk BGA-225	NA/SnPb	1985	2006	2302
	NA/SAC	1 (3103)	23 (3175)	15245 (4521)
Rwk TQFP-208	SnPb/NiPdAu	533	603	1572
	SAC/NiPdAu	148	139	2167
	SACB/NiPdAu	1 (245)	1 (268)	652 (1775)
Rwk TSOP-50	SnPb/SnPb	305	241	584
	SAC/SnCu	534	627	1166
	SACB/SnCu	249	183	539

*NF = Not Enough Failures for the Generation of Weibull N10 and N63Values

(xxxx) = Indicate a Subject Data Interpretation due to Weibull Outlier Points

Appendix C

App Table 2 Solder Performance Comparison for -55C to +125 C Thermal Cycle Testing

Relative Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	0	0	0
	SAC/SAC	+	++	++
	SACB/SAC	++	++	++
	SAC/SnPb	--	--	--
	SACB/SnPb	++	-	-
CLCC-20	SnPb/SnPb	0	0	0
	SAC/SAC	--	--	--
	SACB/SACB	+	+	+
	SAC/SnPb	-	-	--
	SACB/SnPb	0	-	-
TQFP-144	SnPb/Sn	0	0	0
	SAC/Sn	--	--	++
	SACB/Sn	++	++	++
TQFP-208	SnPb/ NiPdAu	0	0	0
	SAC/ NiPdAu	++	++	++
	SACB/ NiPdAu	--	++	++
TSOP-50	SnPb/SnPb	0	0	0
	SAC/SnCu	--	--	-
	SACB/SnCu	+	++	++
	SAC/SnPb	--	--	-
	SACB/SnPb	--	--	--
Rwk BGA-225	NA/SnPb	0	0	0
	NA/SAC	++	++	++
Rwk TQFP-208	SnPb/NiPdAu	0	0	0
	SAC/NiPdAu	--	--	++
	SACB/NiPdAu	--	--	--
Rwk TSOP-50	SnPb/SnPb	0	0	0
	SAC/SnCu	++	++	++
	SACB/SnCu	-	--	-

Legend:
0 = Same as control or <5% difference
+ = 5 to 20%
++ = >20%
- = -5 to -20%
-- = >-20% (red if much greater than -20%)
NA = Not Available (not enough failures)
NT = Not Tested
P = Pending (awaiting data)

Appendix D -55C to +125C Thermal Cycle Raw Data

App Table 3 '"Manufactured"' Test Vehicles Data

Part Description	Failure Data	Cross Reference (board/part #)
BGA-225 with SAC solder, SAC finish, on "Manufactured" board	533, 725, 2014, 2187, 2535, 2762, 2792, 2892, 2968, 3011, 3038, 3048, 3056, 3123, 3154, 3223, 3350, 3420, 3524, 3664, 3664, 3753, 3971, 4386, DNF	88/U43, 88/U06, 88/U04, 85/U55, 89/U18, 87/U55, 88/U55, 85/U04, 86/U04, 86/U55, 87/U06, 86/U06, 89/U43, 88/U18, 85/U43, 89/U55, 89/U06, 85/U06, 86/U18, 87/U43, 89/U04, 87/U04, 86/U43, 85/U18, 87/U18
BGA-225 with SAC solder, Sn/Pb finish, on "Manufactured" board	4, 229, 305, 312, 373, 441, 493, 526, 883, 920, 1272, 1713, 1881, 2041, 2061, 2264, 2278, 2309, 2325, 2432, 2730, DNF, DNF, DNF, DNF	88/U05, 88/U21, 86/U21, 89/U02, 89/U21, 89/U56, 89/U05, 88/U02, 85/U44, 87/U44, 88/U44, 87/U02, 85/U05, 89/U44, 85/U56, 88/U56, 86/U05, 87/U05, 87/U21, 85/U21, 85/U02, 86/U02, 86/U44, 86/U56, 87/U56
BGA-225 with SACB solder, SAC finish, on "Manufactured" board	2894, 2968, 3251, 3260, 3338, 3348, 3350, 3515, 3664, 3666, 3854, 3971, 3971, 4036, 4172, 4214, 4232, 4255, 4387, 4389, 4392, 4443, 4657, DNF, DNF	125/U43, 127/U55, 127/U43, 125/U55, 125/U06, 128/U18, 128/U43, 124/U43, 128/U04, 128/U06, 125/U04, 126/U18, 128/U55, 126/U04, 124/U06, 124/U18, 127/U18, 127/U06, 124/U55, 127/U04, 124/U04, 126/U55, 125/U18, 126/U06, 126/U43
BGA-225 with SACB solder, Sn/Pb finish, on "Manufactured" board	1536, 1570, 1610, 1672, 1723, 1809, 1881, 1882, 2192, 2248, 2274, 2302, 2480, 2500, 2555, 2647, 2649, 2676, 2727, 2757, 2771, 2853, 2917, 3184, DNF	128/U44, 128/U21, 125/U02, 127/U05, 126/U05, 124/U56, 125/U44, 128/U05, 127/U44, 125/U56, 127/U56, 127/U21, 124/U05, 124/U21, 125/U05, 125/U21, 126/U56, 124/U44, 126/U44, 124/U02, 127/U02, 126/U02, 128/U02, 126/U21, 128/U56
BGA-225 with SnPb solder, SnPb finish, on "Manufactured" board	1068, 1348, 1865, 1881, 1902, 1952, 1996, 2120, 2122, 2187, 2189, 2195, 2199, 2227, 2236, 2244, 2292, 2319, 2334, 2381, 2395, 2488, 2536, 2536, 2536, 2561, 2573, 2575, 2680, 2693, 2705, 2706, 2740, 2753, 2756, 2780, 2795, 2808, 2809, 2824, 2886, 2887, 2894, 2903, 2918, 2968, 3046, 3100, 3116, 3130	17/U02, 19/U04, 16/U55, 19/U05, 17/U04, 18/U56, 17/U44, 18/U21, 18/U05, 18/U44, 17/U18, 16/U18, 17/U43, 17/U56, 19/U44, 18/U02, 15/U21, 19/U21, 18/U55, 16/U21, 16/U02, 15/U02, 15/U43, 18/U04, 18/U06, 18/U43, 16/U06, 16/U44, 16/U04, 17/U05, 19/U43, 19/U56, 19/U02, 15/U06, 17/U55, 16/U05, 15/U04, 18/U18, 15/U55, 19/U06, 17/U06, 19/U18, 17/U21, 15/U56, 16/U43, 15/U05, 19/U55, 15/U18, 16/U56, 15/U44
CLCC-20 with SAC solder, SAC finish, on "Manufactured" board	288, 364, 370, 378, 406, 414, 419, 427, 439, 440, 464, 477, 487, 491, 493, 493, 493, 501, 503, 549, 551, 579, 582, 627, 642	87/U52, 85/U10, 87/U14, 85/U17, 86/U45, 88/U17, 88/U52, 87/U17, 89/U45, 86/U14, 88/U10, 89/U17, 89/U14, 88/U14, 85/U14, 85/U45, 89/U10, 86/U10, 86/U52, 87/U45, 89/U52, 87/U10, 86/U17, 85/U52, 88/U45
CLCC-20 with SAC solder, SnPb finish, on "Manufactured" board	377, 381, 393, 414, 439, 446, 451, 460, 481, 493, 493, 505, 533, 533, 533, 553, 554, 559, 574, 612, 618, 666, 700, 783, 826	87/U13, 85/U13, 89/U09, 89/U13, 87/U09, 85/U53, 88/U13, 86/U22, 89/U53, 85/U22, 89/U46, 86/U13, 86/U46, 87/U46, 87/U53, 88/U22, 85/U09, 87/U22, 88/U53, 88/U09, 89/U22, 86/U09, 88/U46, 86/U53, 85/U46
CLCC-20 with SACB solder, SACB finish, on "Manufactured" board	493, 499, 533, 533, 533, 541, 635, 639, 647, 664, 664, 670, 697, 701, 704, 718, 822, 822, 822, 837, 864, 883, 883, 1068, 1147	124/U52, 128/U10, 124/U14, 126/U52, 127/U10, 124/U17, 126/U10, 125/U17, 128/U45, 125/U45, 126/U17, 127/U52, 124/U10, 127/U45, 128/U14, 127/U17, 125/U14, 125/U52, 127/U14, 125/U10, 128/U17, 126/U14, 128/U52, 126/U45, 124/U45
CLCC-20 with SACB solder, SnPb finish, on "Manufactured" board	455, 493, 493, 499, 518, 533, 533, 533, 534, 534, 553, 558, 564, 569, 572, 591, 594, 598, 605, 664, 707, 724, 749, 883, 883	124/U22, 125/U13, 126/U22, 124/U13, 126/U53, 125/U09, 125/U46, 126/U46, 124/U53, 127/U53, 128/U13, 125/U22, 128/U46, 125/U53, 127/U22, 127/U46, 126/U09, 128/U53, 124/U46, 127/U13, 128/U22, 127/U09, 124/U09, 126/U13, 128/U09
CLCC-20 with SnPb solder, Sn/Pb finish, on "Manufactured" board	455, 466, 492, 493, 493, 493, 494, 497, 505, 508, 533, 533, 542, 543, 547, 552, 563, 568, 569, 569, 608, 627, 634, 649, 663, 670, 699, 700, 701, 702, 710, 710, 711, 719, 728, 730, 741, 756, 772, 780, 789, 791, 806, 822, 828, 881, 900, 969, 994, 1187	18/U09, 19/U17, 18/U13, 16/U45, 18/U14, 19/U53, 19/U52, 15/U17, 18/U10, 19/U22, 18/U53, 19/U09, 18/U22, 16/U10, 15/U14, 17/U14, 15/U53, 15/U09, 15/U10, 19/U13, 19/U45, 16/U09, 17/U09, 17/U17, 18/U46, 17/U52, 16/U46, 17/U53, 16/U13, 15/U13, 18/U45, 19/U46, 19/U10, 15/U45, 17/U46,

Part Description	Failure Data	Cross Reference (board/part #)
		18/U17, 16/U14, 16/U22, 16/U17, 16/U53, 19/U14, 16/U52, 15/U22, 17/U10, 18/U52, 15/U52, 17/U22, 15/U46, 17/U45, 17/U13
PDIP-20 with SAC solder, Au/Pd/Ni finish, on "Manufactured" board	576, 835, 1552, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	86/U23, 86/U35, 88/U23, 85/U08, 85/U23, 85/U35, 85/U49, 85/U59, 86/U08, 86/U49, 86/U59, 87/U08, 87/U23, 87/U35, 87/U49, 87/U59, 88/U08, 88/U35, 88/U49, 88/U59, 89/U08, 89/U23, 89/U35, 89/U49, 89/U59
PDIP-20 with SAC solder, Sn finish, on "Manufactured" board	474, 3174, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	88/U11, 86/U30, 85/U11, 85/U30, 85/U38, 85/U51, 85/U63, 86/U11, 86/U38, 86/U51, 86/U63, 87/U11, 87/U30, 87/U38, 87/U51, 87/U63, 88/U30, 88/U38, 88/U51, 88/U63, 89/U11, 89/U30, 89/U38, 89/U51, 89/U63
PDIP-20 with SACB solder, Au/Pd/Ni finish, on "Manufactured" board	879, 1316, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	125/U23, 128/U08, 124/U08, 124/U23, 124/U35, 124/U49, 124/U59, 125/U08, 125/U35, 125/U49, 125/U59, 126/U08, 126/U23, 126/U35, 126/U49, 126/U59, 127/U08, 127/U23, 127/U35, 127/U49, 127/U59, 128/U23, 128/U35, 128/U49, 128/U59
PDIP-20 with SACB solder, Sn finish, on "Manufactured" board	1474, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	124/U30, 124/U11, 124/U38, 124/U51, 124/U63, 125/U11, 125/U30, 125/U38, 125/U51, 125/U63, 126/U11, 126/U30, 126/U38, 126/U51, 126/U63, 127/U11, 127/U30, 127/U38, 127/U51, 127/U63, 128/U11, 128/U30, 128/U38, 128/U51, 128/U63
PDIP-20 with SnPb solder, Au/Pd/Ni finish, on "Manufactured" board	620, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	15/U23, 15/U08, 15/U35, 15/U49, 15/U59, 16/U08, 16/U23, 16/U35, 16/U49, 16/U59, 17/U08, 17/U23, 17/U35, 17/U49, 17/U59, 18/U08, 18/U23, 18/U35, 18/U49, 18/U59, 19/U08, 19/U23, 19/U35, 19/U49, 19/U59
PDIP-20 with SnPb solder, Sn finish, on "Manufactured" board	493, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	15/U11, 15/U30, 15/U38, 15/U51, 15/U63, 16/U11, 16/U30, 16/U38, 16/U51, 16/U63, 17/U11, 17/U30, 17/U38, 17/U51, 17/U63, 18/U11, 18/U30, 18/U38, 18/U51, 18/U63, 19/U11, 19/U30, 19/U38, 19/U51, 19/U63
PLCC-20 with SAC solder, Sn finish, on "Manufactured" board	324, 327, 798, 1469, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	86/U27, 89/U27, 88/U15, 86/U28, 85/U15, 85/U27, 85/U28, 85/U47, 85/U54, 86/U15, 86/U47, 86/U54, 87/U15, 87/U27, 87/U28, 87/U47, 87/U54, 88/U27, 88/U28, 88/U47, 88/U54, 89/U15, 89/U28, 89/U47, 89/U54
PLCC-20 with SACB solder, Sn finish, on "Manufactured" board	DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	124/U15, 124/U27, 124/U28, 124/U47, 124/U54, 125/U15, 125/U27, 125/U28, 125/U47, 125/U54, 126/U15, 126/U27, 126/U28, 126/U47, 126/U54, 127/U15, 127/U27, 127/U28, 127/U47, 127/U54, 128/U15, 128/U27, 128/U28, 128/U47, 128/U54
PLCC-20 with SnPb solder, Sn finish, on "Manufactured" board	1068, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	17/U27, 15/U15, 15/U27, 15/U28, 15/U47, 15/U54, 16/U15, 16/U27, 16/U28, 16/U47, 16/U54, 17/U15, 17/U28, 17/U47, 17/U54, 18/U15, 18/U27, 18/U28, 18/U47, 18/U54, 19/U15, 19/U27, 19/U28, 19/U47, 19/U54
PTH with SAC solder, PTH finish, on "Manufactured" board	DNF, DNF, DNF, DNF, DNF	85/U64, 86/U64, 87/U64, 88/U64, 89/U64
PTH with SACB solder, PTH finish, on "Manufactured" board	2568, DNF, DNF, DNF, DNF	126/U64, 124/U64, 125/U64, 127/U64, 128/U64
PTH with SnPb solder, PTH finish, on "Manufactured" board	DNF, DNF, DNF, DNF, DNF	15/U64, 16/U64, 17/U64, 18/U64, 19/U64

Part Description	Failure Data	Cross Reference (board/part #)
TQFP-144 with SAC solder, Sn finish, on "Manufactured" board	245, 498, 639, 1368, 1519, 1527, 1799, 1836, 1881, 1993, 2551, 2620, 2764, 2826, 3034, 3093, 3631, 3923, 4041, 4386, DNF, DNF, DNF, DNF, DNF	88/U01, 88/U41, 86/U20, 88/U07, 89/U01, 88/U20, 89/U20, 89/U58, 89/U07, 89/U41, 85/U20, 85/U07, 87/U07, 85/U01, 86/U01, 87/U01, 87/U20, 87/U41, 85/U41, 87/U58, 85/U58, 86/U07, 86/U41, 86/U58, 88/U58
TQFP-144 with SACB solder, Sn finish, on "Manufactured" board	2605, 2641, 2663, 2680, 2800, 2887, 2889, 3251, 3251, 3261, 3294, 3378, 3664, 3665, 3687, 4025, 4441, 4556, DNF, DNF, DNF, DNF, DNF, DNF, DNF	126/U01, 127/U20, 128/U01, 126/U41, 125/U58, 126/U07, 128/U20, 124/U07, 127/U07, 127/U01, 125/U07, 125/U01, 128/U07, 124/U01, 126/U20, 125/U20, 126/U58, 128/U41, 124/U20, 124/U41, 124/U58, 125/U41, 127/U41, 127/U58, 128/U58
TQFP-144 with SnPb solder, Sn finish, on "Manufactured" board	1473, 1949, 2125, 2187, 2197, 2239, 2339, 2348, 2359, 2392, 2423, 2441, 2536, 2536, 2583, 2592, 2615, 2680, 2734, 2888, 2888, 2945, 2981, 3058, 3251	18/U07, 16/U07, 18/U41, 15/U01, 19/U41, 19/U58, 19/U20, 16/U01, 19/U07, 19/U01, 15/U41, 18/U01, 15/U58, 18/U58, 17/U20, 15/U07, 18/U20, 17/U41, 15/U20, 16/U20, 17/U58, 16/U41, 17/U07, 17/U01, 16/U58
TQFP-208 with SAC solder, Au/Pd/Ni finish, on "Manufactured" board	704, 834, 2833, 3379, 3697, 3753, 3863, 4027, 4053, 4255, 4386, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	86/U57, 86/U03, 88/U34, 87/U34, 88/U03, 89/U03, 87/U48, 89/U31, 87/U03, 87/U31, 89/U57, 85/U03, 85/U31, 85/U34, 85/U48, 85/U57, 86/U31, 86/U34, 86/U48, 87/U57, 88/U31, 88/U48, 88/U57, 89/U34, 89/U48
TQFP-208 with SACB solder, Au/Pd/Ni finish, on "Manufactured" board	506, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	125/U31, 124/U03, 124/U31, 124/U34, 124/U48, 124/U57, 125/U03, 125/U34, 125/U48, 125/U57, 126/U03, 126/U31, 126/U34, 126/U48, 126/U57, 127/U03, 127/U31, 127/U34, 127/U48, 127/U57, 128/U03, 128/U31, 128/U34, 128/U48, 128/U57
TQFP-208 with SnPb solder, Au/Pd/Ni finish, on "Manufactured" board	1068, 2537, 2707, 2888, 2940, 2943, 3251, 3260, 3356, 3357, 3375, 3379, 3444, 3483, 3524, 3666, 3874, 3886, 3971, 4078, 4256, 4268, 4386, 4465, 4554	17/U31, 16/U03, 19/U03, 16/U48, 18/U03, 15/U03, 17/U57, 18/U31, 15/U57, 19/U48, 15/U48, 19/U57, 19/U34, 16/U57, 18/U57, 18/U48, 15/U34, 17/U34, 17/U03, 15/U31, 17/U48, 16/U31, 18/U34, 16/U34, 19/U31
TSOP-50 with SAC solder, Sn/Cu finish, on "Manufactured" board	440, 676, 678, 757, 765, 827, 830, 840, 848, 859, 880, 883, 908, 956, 967, 1049, 1068, 1110, 1136, 1187, 1189, 1256, 1269, 1519, DNF	88/U61, 86/U12, 88/U29, 88/U12, 87/U12, 89/U12, 87/U29, 86/U29, 89/U29, 85/U12, 89/U39, 85/U29, 87/U61, 88/U25, 88/U39, 87/U39, 87/U25, 89/U25, 85/U61, 85/U39, 86/U61, 85/U25, 89/U61, 86/U39, 86/U25
TSOP-50 with SAC solder, Sn/Pb finish, on "Manufactured" board	382, 433, 671, 726, 786, 842, 872, 883, 883, 883, 883, 883, 1014, 1068, 1068, 1069, 1187, 1187, 1187, 1187, 1187, 1187, 1190, 1316, DNF	89/U40, 86/U40, 88/U26, 89/U26, 87/U26, 86/U62, 85/U16, 85/U26, 86/U16, 86/U24, 86/U26, 89/U16, 88/U62, 87/U62, 89/U24, 85/U24, 85/U40, 87/U16, 87/U40, 88/U16, 88/U24, 89/U62, 88/U40, 85/U62, 87/U24
TSOP-50 with SACB solder, Sn/Cu finish, on "Manufactured" board	884, 1188, 1263, 1278, 1323, 1380, 1519, 1523, 1583, 1653, 1665, 1700, 1779, 1881, 1881, 1881, 1881, 1964, 2187, 2188, 2213, 2225, 2249, 2663, 2674	124/U12, 125/U12, 126/U12, 127/U12, 128/U29, 125/U29, 124/U25, 126/U29, 128/U25, 126/U25, 125/U25, 124/U29, 128/U61, 126/U39, 126/U61, 127/U29, 128/U39, 127/U39, 125/U39, 124/U39, 127/U61, 124/U61, 127/U25, 128/U12, 125/U61
TSOP-50 with SACB solder, Sn/Pb finish, on Manufactured board	157, 169, 203, 216, 280, 312, 321, 335, 338, 343, 419, 424, 442, 493, 493, 533, 533, 534, 537, 537, 622, 668, 680, 693, 2663	126/U26, 126/U16, 124/U16, 127/U16, 125/U26, 124/U26, 125/U16, 128/U16, 128/U62, 127/U26, 126/U62, 128/U24, 127/U24, 125/U62, 127/U40, 125/U24, 126/U40, 128/U40, 124/U24, 124/U40, 124/U62, 126/U24, 125/U40, 127/U62, 128/U26
TSOP-50 with SnPb solder, SnPb finish, on Manufactured board	822, 822, 824, 837, 883, 883, 883, 890, 899, 910, 910, 920, 938, 953, 963, 981, 988, 1021, 1033, 1034, 1068, 1091, 1109, 1111, 1115, 1147, 1154, 1187, 1187, 1187, 1187, 1187, 1187, 1187, 1187, 1188, 1192, 1195, 1232, 1244, 1250, 1255, 1260, 1370, 1382, 1449, 1519, 1519, DNF, DNF	18/U16, 19/U62, 19/U40, 15/U24, 18/U26, 18/U29, 18/U62, 16/U26, 17/U39, 19/U26, 19/U29, 16/U25, 19/U61, 17/U61, 16/U24, 16/U61, 19/U16, 17/U26, 17/U40, 19/U25, 16/U62, 17/U29, 17/U62, 16/U12, 18/U24, 15/U25, 15/U29, 15/U40, 15/U62, 16/U40, 17/U16, 17/U24, 18/U40, 19/U24, 19/U39, 17/U25, 18/U61, 15/U39, 15/U26, 18/U25, 18/U12, 17/U12, 19/U12, 16/U29, 16/U39, 15/U12, 15/U16, 15/U61, 16/U16, 18/U39

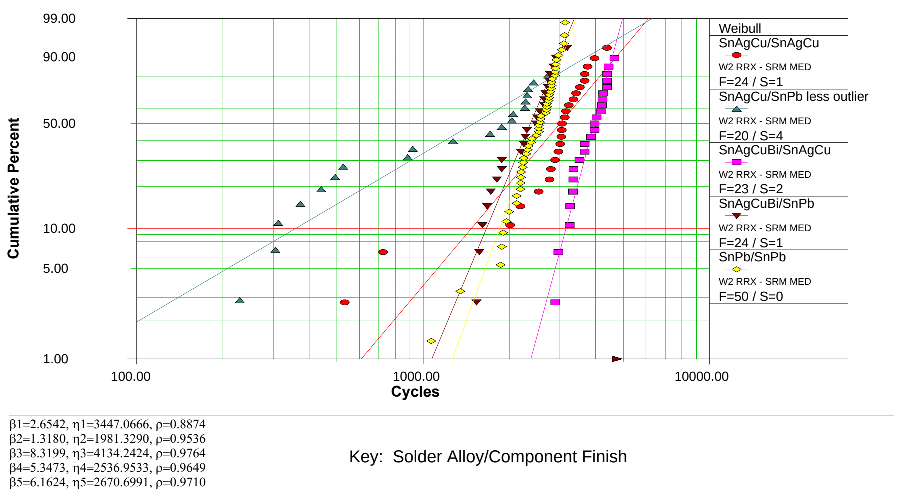
App Table 4 'Reworked' Test Vehicles Data

Part Description	Failure Data	Cross Reference (board/part #)
BGA-225 with SnPb solder, SAC finish, on "Rework" board	361, 538, 822, 1068, 1068, 1187, 1188, 1189, 1189, 1189, 1190, 1221, 1408, 1410, 1474, 1519, 1707, 1708, 1963, 2046, 2336, 2536, 2840, 2888, 2888, 2907, 2976, 3068, 3181, 3252, 3254, 3318, 3387, 3664, 3664, 3664, 3886, 3989, 4045, 4172, 4185, 4283, 4386, 4390, 4392, 4588, 4664, 4704, 4737, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	166/U44, 193/U21, 191/U21, 164/U44, 195/U55, 163/U55, 191/U44, 164/U05, 193/U05, 194/U05, 195/U21, 191/U06, 193/U06, 167/U21, 195/U06, 166/U02, 192/U02, 166/U05, 166/U21, 164/U21, 164/U06, 193/U55, 194/U44, 192/U21, 193/U56, 195/U56, 191/U05, 193/U43, 163/U56, 192/U05, 193/U44, 192/U56, 165/U02, 191/U43, 194/U55, 194/U56, 163/U05, 163/U44, 191/U56, 164/U43, 192/U55, 165/U55, 194/U06, 192/U43, 163/U06, 164/U56, 167/U43, 165/U43, 191/U02, 163/U02, 164/U02, 167/U02, 193/U02, 194/U02, 195/U02, 165/U05, 167/U05, 195/U05, 165/U06, 166/U06, 167/U06, 192/U06, 163/U21, 165/U21, 194/U21, 163/U43, 166/U43, 194/U43, 195/U43, 165/U44, 167/U44, 192/U44, 195/U44, 164/U55, 166/U55, 167/U55, 191/U55, 165/U56, 166/U56, 167/U56
BGA-225 with SnPb solder, SAC finish, on "Rework" board, reworked with SAC	1, 4, 822, 3103, 3255, 3350, 3397, 3664, 3665, 3778, 4178, 4441, 4629, 4657, 4657, 4702, 4735, DNF, DNF, DNF	195/U04, 167/U18, 191/U04, 166/U04, 164/U04, 191/U18, 193/U18, 167/U04, 194/U04, 192/U04, 193/U04, 195/U18, 194/U18, 163/U04, 192/U18, 165/U04, 166/U18, 163/U18, 164/U18, 165/U18
BGA-225 with SnPb solder, SnPb finish, on "Rework" board	533, 1762, 1802, 1907, 2008, 2012, 2060, 2061, 2074, 2123, 2123, 2133, 2187, 2188, 2232, 2285, 2320, 2327, 2335, 2376, 2384, 2392, 2404, 2462, 2536, 2548, 2555, 2564, 2590, 2600, 2659, 2667, 2701, 2718, 2780, 2806, 2833, 2887, 2896, DNF	58/U43, 59/U05, 57/U02, 56/U05, 60/U06, 59/U02, 58/U06, 57/U06, 59/U43, 56/U06, 60/U56, 57/U05, 57/U44, 58/U02, 60/U02, 56/U02, 59/U55, 56/U44, 56/U55, 56/U21, 57/U56, 57/U21, 59/U56, 59/U06, 60/U44, 60/U05, 58/U05, 60/U43, 57/U43, 58/U21, 60/U21, 59/U44, 59/U21, 60/U55, 58/U55, 57/U55, 58/U56, 56/U43, 58/U44, 56/U56
BGA-225 with SnPb solder, SnPb finish, on "Rework" board, reworked with SnPb	1985, 2084, 2149, 2172, 2188, 2263, 2309, 2336, 2346, 2507	58/U04, 59/U18, 60/U04, 58/U18, 57/U18, 57/U04, 56/U04, 56/U18, 60/U18, 59/U04
CLCC-20 with SnPb solder, Sn/Pb finish, on "Rework" board	423, 467, 472, 484, 493, 493, 493, 493, 493, 493, 509, 530, 533, 533, 533, 549, 559, 577, 577, 580, 593, 618, 642, 642, 649, 654, 662, 663, 667, 681, 684, 695, 700, 707, 715, 753, 773, 806, 806, 822, 841, 844, 883, 883, 883, 886, 893, 925, 926, 953	60/U17, 60/U09, 58/U17, 58/U52, 58/U09, 58/U13, 60/U13, 59/U17, 58/U22, 60/U53, 56/U17, 60/U22, 56/U10, 57/U13, 57/U14, 59/U09, 60/U14, 56/U09, 58/U14, 60/U10, 58/U46, 60/U46, 56/U13, 56/U52, 58/U53, 56/U53, 58/U10, 56/U46, 57/U22, 56/U22, 58/U45, 60/U45, 57/U09, 59/U53, 56/U14, 57/U17, 57/U10, 56/U45, 59/U52, 57/U53, 60/U52, 59/U45, 57/U45, 57/U46, 57/U52, 59/U14, 59/U13, 59/U46, 59/U10, 59/U22
CLCC-20 with SnPb solder, SnAgCu finish, on "Rework" board	266, 283, 297, 305, 305, 305, 305, 305, 305, 305, 308, 308, 308, 309, 319, 323, 324, 326, 328, 330, 333, 333, 335, 338, 338, 342, 346, 347, 349, 351, 371, 373, 374, 374, 386, 387, 396, 398, 416, 424, 425, 447, 447, 448, 459, 493, 493, 493, 533, 587	164/U22, 164/U10, 165/U10, 163/U13, 163/U17, 163/U22, 163/U45, 163/U46, 166/U46, 167/U46, 166/U22, 165/U52, 164/U53, 166/U45, 164/U45, 164/U09, 167/U45, 165/U17, 163/U10, 167/U52, 165/U09, 164/U14, 163/U52, 164/U13, 165/U13, 165/U53, 166/U53, 167/U17, 166/U13, 167/U09, 167/U10, 167/U14, 163/U09, 166/U52, 164/U17, 164/U52, 167/U22, 167/U53, 163/U53, 165/U45, 166/U09, 165/U14, 165/U46, 166/U10, 167/U13, 163/U14, 165/U22, 164/U46, 166/U17, 166/U14
CLCC-20 with SnPb solder, SnAgCuBi finish, on "Rework" board	58, 202, 245, 286, 289, 305, 308, 317, 317, 320, 323, 324, 329, 333, 334, 340, 345, 346, 355, 356, 358, 359, 361, 367, 368, 368, 369, 369, 379, 382, 383, 384, 392, 396, 412, 417, 418, 419, 427, 434, 445, 454, 464, 483, 492, 493, 499, 508, 515, 647	194/U10, 193/U17, 192/U22, 192/U53, 194/U45, 193/U45, 193/U10, 194/U17, 194/U53, 195/U14, 195/U09, 194/U52, 194/U22, 191/U22, 195/U13, 194/U09, 195/U22, 195/U10, 195/U17, 193/U46, 194/U46, 194/U13, 193/U13, 195/U52, 191/U14, 192/U14, 192/U10, 192/U52, 192/U46, 195/U46, 191/U13, 192/U17, 195/U45, 192/U09, 191/U09, 193/U52, 191/U17, 194/U14, 193/U53, 193/U22, 192/U45, 191/U45, 192/U13, 193/U09, 195/U53, 193/U14, 191/U53, 191/U10, 191/U52, 191/U46

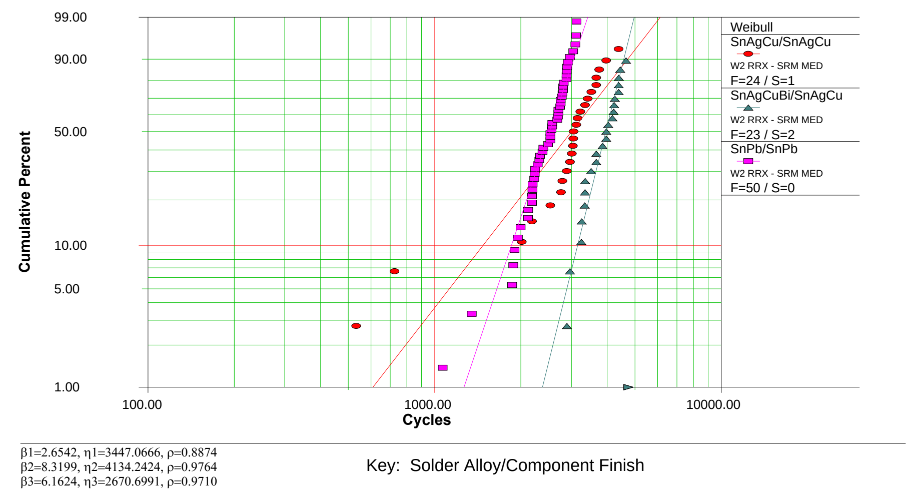
Part Description	Failure Data	Cross Reference (board/part #)
PDIP-20 with SnPb solder, Au/Pd/Ni finish, on “Rework” board	1117, 1956, 2408, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	164/U08, 194/U49, 59/U08, 56/U08, 57/U08, 58/U08, 60/U08, 163/U08, 165/U08, 166/U08, 167/U08, 191/U08, 192/U08, 193/U08, 194/U08, 195/U08, 56/U35, 57/U35, 58/U35, 59/U35, 60/U35, 163/U35, 164/U35, 165/U35, 166/U35, 167/U35, 191/U35, 192/U35, 193/U35, 194/U35, 195/U35, 56/U49, 57/U49, 58/U49, 59/U49, 60/U49, 163/U49, 164/U49, 165/U49, 166/U49, 167/U49, 191/U49, 192/U49, 193/U49, 195/U49
PDIP-20 with SnPb solder, Au/Pd/Ni finish, on “Rework” board, reworked with SnCuNi	842, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	191/U59, 56/U23, 57/U23, 58/U23, 59/U23, 60/U23, 163/U23, 164/U23, 165/U23, 166/U23, 167/U23, 191/U23, 192/U23, 193/U23, 194/U23, 195/U23, 56/U59, 57/U59, 58/U59, 59/U59, 60/U59, 163/U59, 164/U59, 165/U59, 166/U59, 167/U59, 192/U59, 193/U59, 194/U59, 195/U59
PDIP-20 with SnPb solder, Sn finish, on “Rework” board	883, 1162, 1517, 1519, 1589, 1595, 1881, 2536, 2536, 3006, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	60/U30, 164/U51, 194/U51, 191/U51, 194/U63, 191/U63, 194/U38, 60/U63, 164/U63, 194/U30, 56/U11, 57/U11, 58/U11, 59/U11, 60/U11, 163/U11, 164/U11, 165/U11, 166/U11, 167/U11, 191/U11, 192/U11, 193/U11, 194/U11, 195/U11, 56/U30, 57/U30, 58/U30, 59/U30, 163/U30, 164/U30, 165/U30, 166/U30, 167/U30, 191/U30, 192/U30, 193/U30, 195/U30, 56/U38, 57/U38, 58/U38, 59/U38, 60/U38, 163/U38, 164/U38, 165/U38, 166/U38, 167/U38, 191/U38, 192/U38, 193/U38, 195/U38, 56/U51, 57/U51, 58/U51, 59/U51, 60/U51, 163/U51, 165/U51, 166/U51, 167/U51, 192/U51, 193/U51, 195/U51, 56/U63, 57/U63, 58/U63, 59/U63, 163/U63, 165/U63, 166/U63, 167/U63, 192/U63, 193/U63, 195/U63
PLCC-20 with SnPb solder, Sn finish, on “Rework” board	1068, 1187, 4327, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	193/U47, 192/U27, 163/U27, 56/U15, 57/U15, 58/U15, 59/U15, 60/U15, 163/U15, 164/U15, 165/U15, 166/U15, 167/U15, 191/U15, 192/U15, 193/U15, 194/U15, 195/U15, 56/U27, 57/U27, 58/U27, 59/U27, 60/U27, 164/U27, 165/U27, 166/U27, 167/U27, 191/U27, 193/U27, 194/U27, 195/U27, 56/U28, 57/U28, 58/U28, 59/U28, 60/U28, 163/U28, 164/U28, 165/U28, 166/U28, 167/U28, 191/U28, 192/U28, 193/U28, 194/U28, 195/U28, 56/U47, 57/U47, 58/U47, 59/U47, 60/U47, 163/U47, 164/U47, 165/U47, 166/U47, 167/U47, 191/U47, 192/U47, 194/U47, 195/U47, 56/U54, 57/U54, 58/U54, 59/U54, 60/U54, 163/U54, 164/U54, 165/U54, 166/U54, 167/U54, 191/U54, 192/U54, 193/U54, 194/U54, 195/U54
PTH with SnPb solder, PTH finish, on “Rework” board	1779, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF	163/U64, 56/U64, 57/U64, 58/U64, 59/U64, 60/U64, 164/U64, 165/U64, 166/U64, 167/U64, 191/U64, 192/U64, 193/U64, 194/U64, 195/U64
TQFP-144 with SnPb solder, Sn finish, on “Rework” board	1068, 1187, 1319, 1426, 1454, 1467, 1519, 1522, 1528, 1532, 1534, 1542, 1551, 1574, 1575, 1577, 1582, 1606, 1615, 1631, 1643, 1654, 1671, 1677, 1683, 1686, 1696, 1725, 1731, 1757, 1765, 1783, 1789, 1881, 1881, 1881, 1881, 1881, 1881, 1881, 1881, 1881, 1881, 1881, 1891, 1891, 1904, 1928, 1942, 1943, 1943, 1946, 1956, 1980, 2064, 2085, 2105, 2105, 2167, 2170, 2176, 2187, 2187, 2188, 2200, 2209, 2309, 2324, 2326, 2328, 2336, 2438, 2536, DNF, DNF	164/U20, 163/U01, 192/U01, 193/U01, 58/U58, 58/U01, 191/U01, 193/U41, 192/U20, 57/U07, 193/U58, 193/U07, 59/U01, 166/U58, 191/U07, 165/U58, 192/U41, 165/U01, 60/U01, 195/U01, 166/U01, 58/U07, 192/U07, 194/U01, 167/U58, 58/U20, 194/U07, 56/U01, 192/U58, 194/U20, 164/U07, 191/U20, 164/U58, 164/U01, 56/U07, 59/U07, 60/U07, 167/U07, 195/U07, 56/U20, 165/U20, 193/U20, 166/U41, 167/U41, 166/U07, 195/U20, 191/U41, 167/U01, 57/U01, 60/U20, 163/U58, 57/U58, 56/U58, 164/U41, 58/U41, 163/U07, 57/U20, 194/U58, 59/U58, 56/U41, 60/U58, 195/U41, 191/U58, 59/U41, 60/U41, 194/U41, 59/U20, 167/U20, 166/U20, 163/U41, 163/U20, 57/U41, 195/U58, 165/U07, 165/U41

Part Description	Failure Data	Cross Reference (board/part #)
TQFP-208 with SnPb solder, Au/Pd/Ni finish, on "Rework" board	1093, 1537, 1800, 1881, 1881, 1881, 1920, 1927, 1954, 1968, 2126, 2187, 2187, 2190, 2202, 2241, 2246, 2253, 2310, 2440, 2449, 2535, 2536, 2537, 2537, 2545, 2640, 2691, 2700, 2711, 2712, 2752, 2775, 2810, 2855, 2915, 2918, 3094, 3094, 3268, 3339, 3339, 3339, 3349, DNF	59/U34, 193/U48, 56/U48, 193/U31, 164/U48, 192/U48, 167/U48, 166/U48, 192/U31, 163/U48, 194/U48, 60/U48, 195/U48, 60/U31, 59/U48, 191/U31, 166/U31, 165/U31, 167/U31, 193/U34, 194/U31, 191/U48, 58/U31, 59/U31, 58/U48, 57/U48, 60/U34, 195/U31, 56/U31, 167/U34, 56/U34, 194/U34, 166/U34, 164/U31, 192/U34, 57/U34, 163/U31, 58/U34, 163/U34, 195/U34, 57/U31, 164/U34, 191/U34, 165/U34, 165/U48
TQFP-208 with SnPb solder, Au/Pd/Ni finish, on "Rework" board, reworked with SAC	1, 1, 21, 85, 148, 181, 245, 423, 533, 671, 822, 822, 860, 1187, 1219, 1237, 1331, 1519, 1519, 1519, 1519, 1881, 1881, 1890, 2303, 2758, 2888, 3753, 3846, DNF	191/U03, 195/U03, 194/U03, 193/U03, 166/U03, 164/U03, 192/U03, 167/U03, 57/U03, 165/U03, 58/U57, 192/U57, 57/U57, 58/U03, 60/U03, 163/U03, 167/U57, 56/U03, 59/U03, 59/U57, 193/U57, 56/U57, 195/U57, 194/U57, 191/U57, 60/U57, 165/U57, 163/U57, 166/U57, 164/U57
TSOP-50 with SnPb solder, Sn/Cu finish, on "Rework" board, reworked with SAC	249, 250, 254, 365, 392, 407, 493, 534, 536, 578, 749, 822, 1068, 1069, 1110, 1187, 1187, 1192, 1223, 1519	193/U25, 195/U12, 193/U12, 191/U12, 191/U25, 194/U12, 194/U25, 163/U25, 195/U25, 192/U25, 166/U12, 163/U12, 165/U12, 166/U25, 164/U12, 192/U12, 167/U25, 164/U25, 167/U12, 165/U25
TSOP-50 with SnPb solder, SnCu finish, on "Rework" board	1, 324, 533, 558, 561, 562, 563, 581, 590, 595, 617, 623, 623, 637, 645, 657, 672, 675, 682, 684, 687, 688, 690, 695, 704, 706, 714, 719, 727, 746, 750, 762, 773, 783, 784, 796, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 822, 824, 831, 832, 833, 842, 853, 856, 861, 868, 869, 878, 883, 883, 883, 883, 889, 909, 945, 1187, 1187, 1187	163/U26, 193/U62, 165/U62, 163/U29, 194/U61, 166/U26, 191/U16, 195/U26, 192/U26, 195/U62, 166/U62, 191/U26, 195/U39, 194/U16, 164/U40, 164/U26, 192/U39, 195/U29, 194/U26, 193/U26, 164/U62, 166/U40, 193/U16, 192/U16, 193/U40, 194/U29, 191/U62, 165/U40, 164/U61, 167/U39, 167/U26, 167/U62, 164/U16, 191/U29, 192/U61, 192/U29, 163/U16, 163/U24, 164/U24, 165/U24, 167/U24, 192/U24, 195/U24, 165/U26, 167/U29, 164/U39, 165/U39, 166/U39, 193/U39, 194/U39, 167/U40, 195/U40, 163/U61, 165/U61, 167/U61, 195/U61, 163/U62, 192/U62, 194/U62, 194/U24, 195/U16, 166/U29, 165/U29, 193/U61, 166/U16, 163/U40, 166/U61, 192/U40, 193/U29, 191/U24, 165/U16, 167/U16, 191/U39, 191/U61, 164/U29, 193/U24, 166/U24, 163/U39, 191/U40, 194/U40
TSOP-50 with SnPb solder, SnPb finish, on "Rework" board	552, 566, 578, 589, 608, 655, 667, 667, 680, 700, 723, 759, 771, 773, 781, 797, 803, 822, 822, 822, 822, 822, 822, 822, 825, 825, 879, 883, 883, 883, 883, 883, 883, 883, 883, 1068, 1118, 1131, 1187, 1187	59/U16, 59/U26, 57/U29, 58/U24, 60/U24, 60/U62, 56/U16, 56/U39, 57/U16, 56/U24, 56/U40, 59/U40, 59/U39, 58/U16, 59/U62, 59/U61, 58/U29, 59/U24, 56/U29, 57/U40, 58/U40, 58/U61, 56/U62, 58/U62, 56/U61, 60/U61, 60/U39, 60/U16, 57/U24, 56/U26, 58/U26, 60/U26, 57/U39, 58/U39, 60/U40, 57/U26, 57/U61, 57/U62, 59/U29, 60/U29

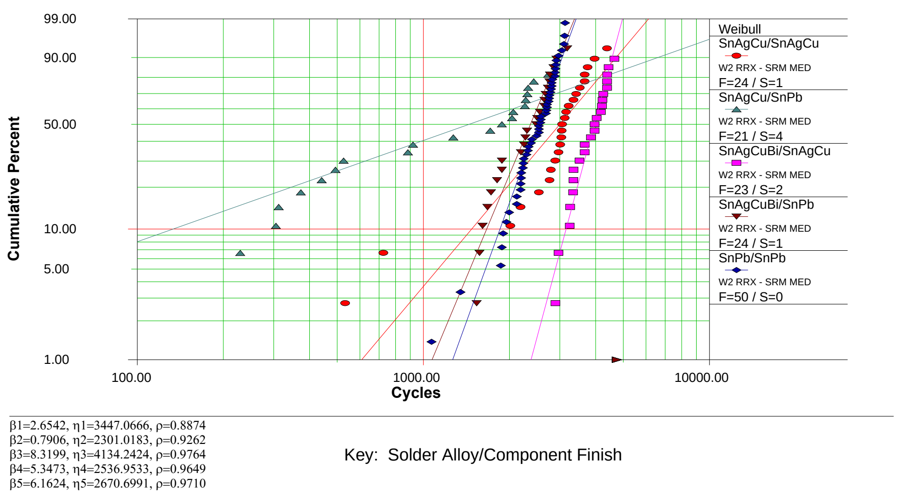
Appendix E Weibull Charts “Manufactured” Test Vehicles



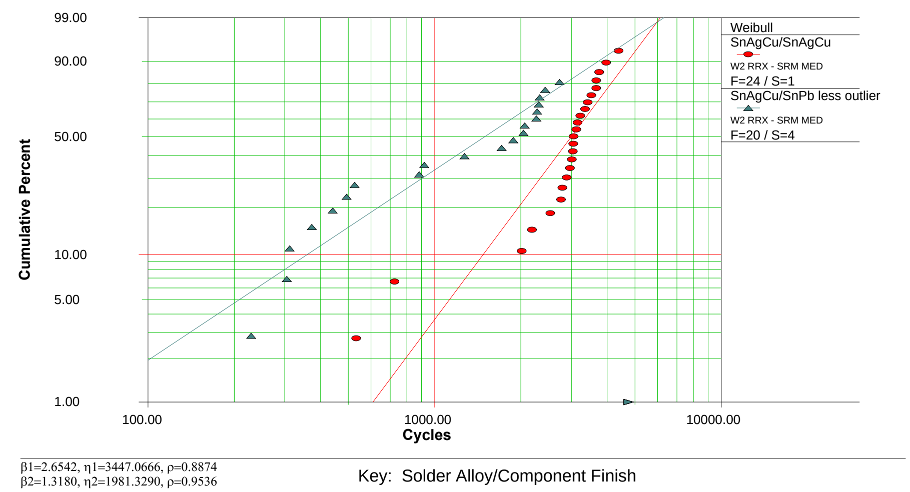
App Fig 3 BGA-225 all combinations less outlier test results for the “Manufactured” test vehicles (170°C Tg)



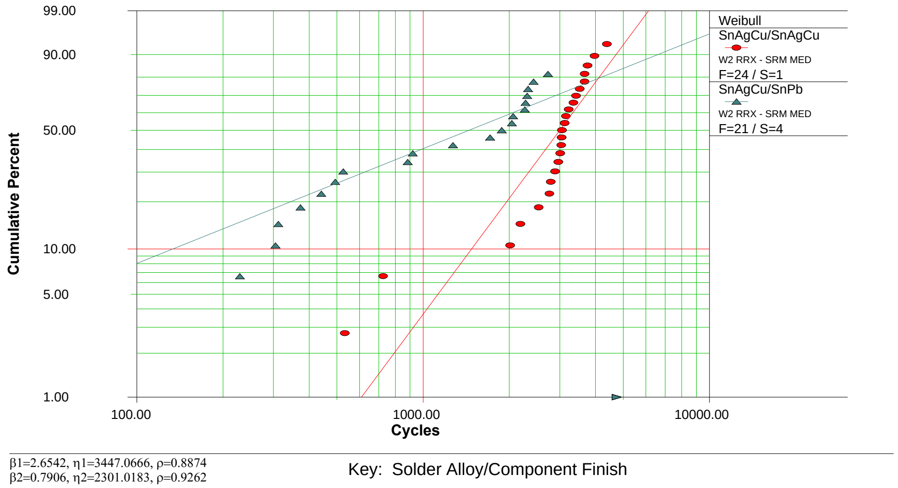
App Fig 5 BGA-225 Pbfree versus SnPb test results for the “Manufactured” test vehicles (170°C Tg)



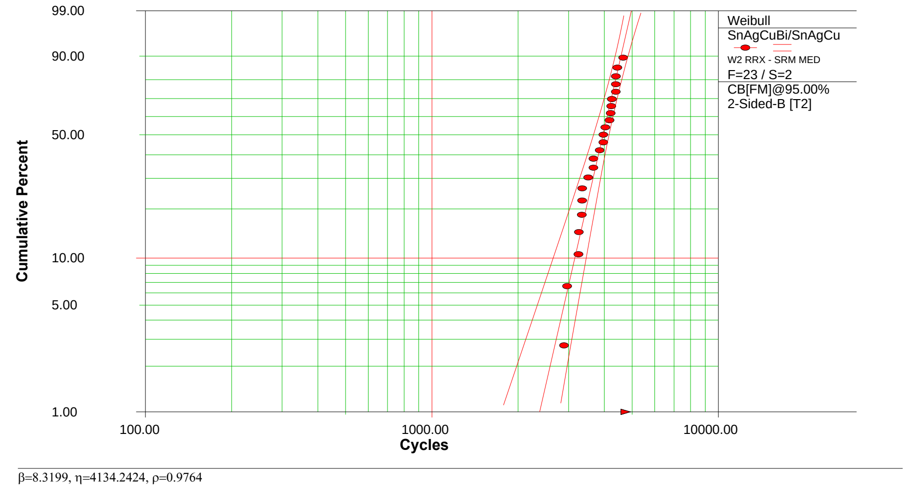
App Fig 4 BGA-225 all combinations test results for the “Manufactured” test vehicles (170°C Tg)



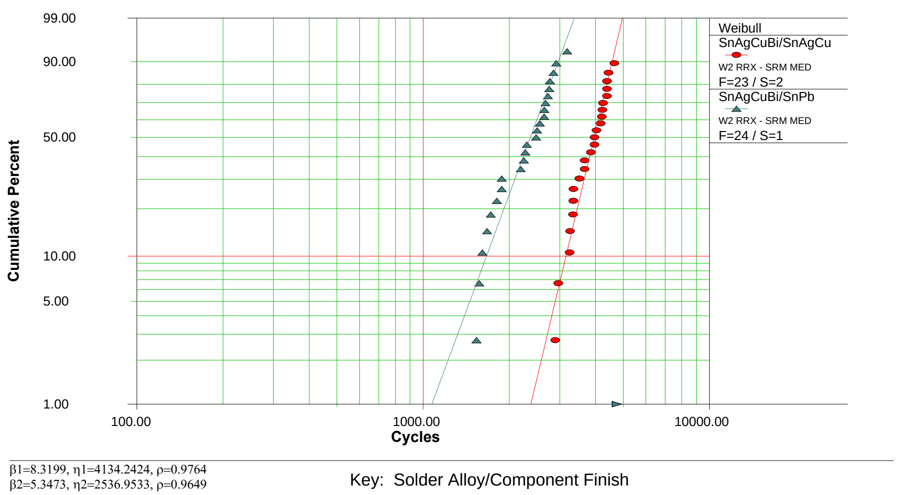
App Fig 6 BGA-225 SAC less outlier test results for the “Manufactured” test vehicles (170°C Tg)



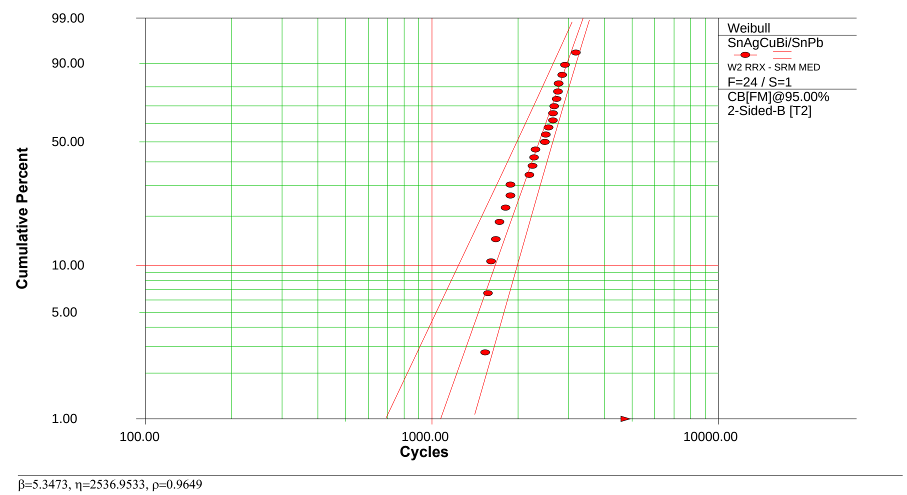
App Fig 7 BGA-225 SAC test results for the "Manufactured" test vehicles (170°C Tg)



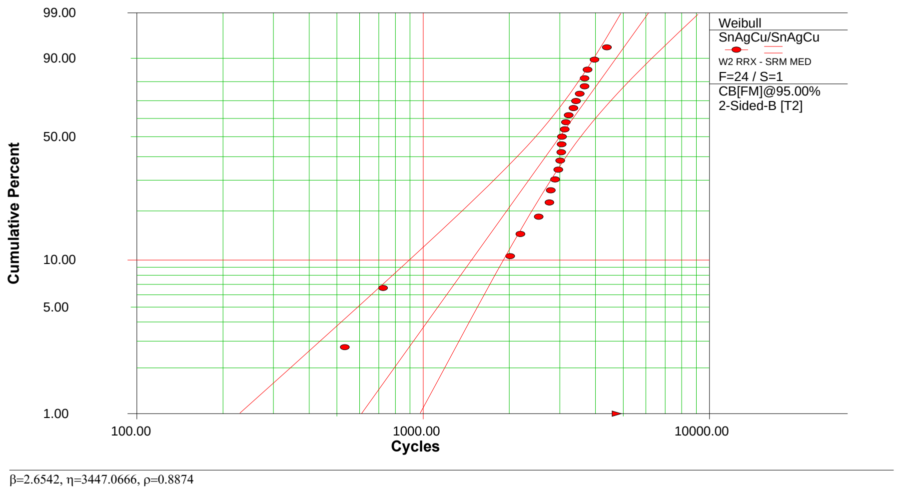
App Fig 9 BGA-225 SACB-SAC test results comparison for the "Manufactured" test vehicles (170°C Tg)



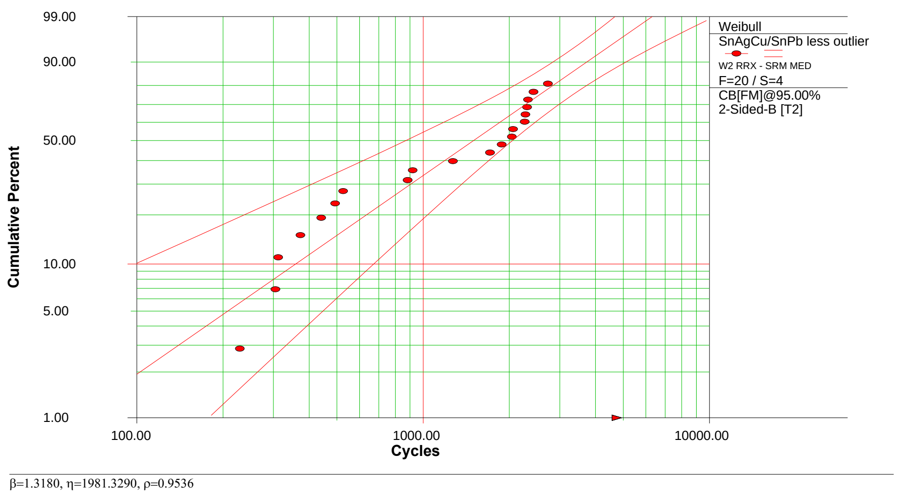
App Fig 8 BGA-225 SACB test results for the "Manufactured" test vehicles (170°C Tg)



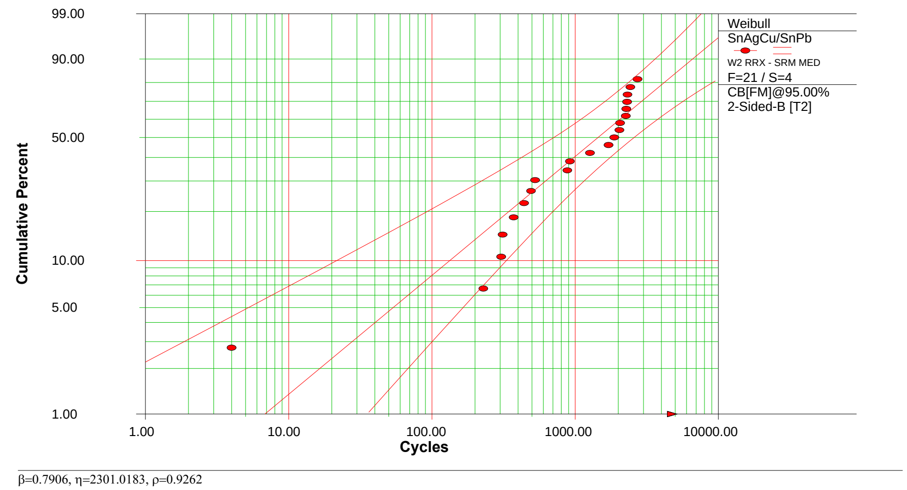
App Fig 10 BGA-225 SACB-SnPb test results comparison for the "Manufactured" test vehicles (170°C Tg)



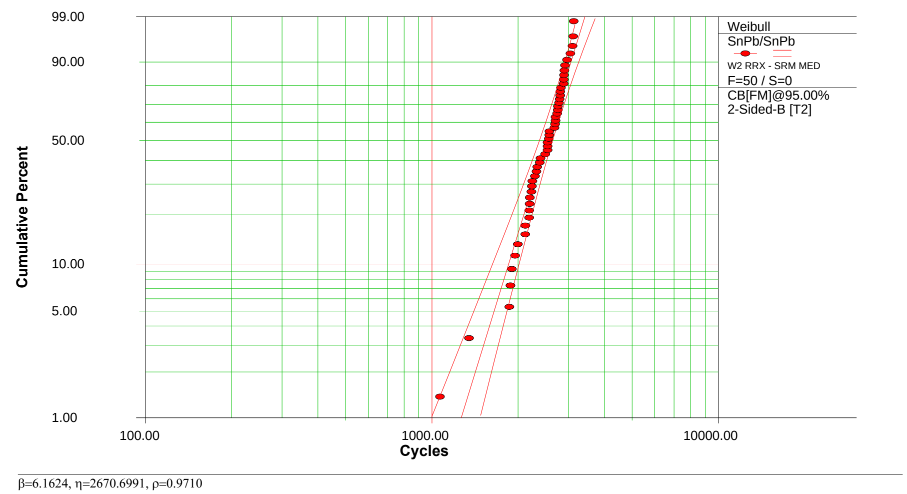
App Fig 11 BGA-225 SAC-SAC test results for the "Manufactured" test vehicles (170°C Tg)



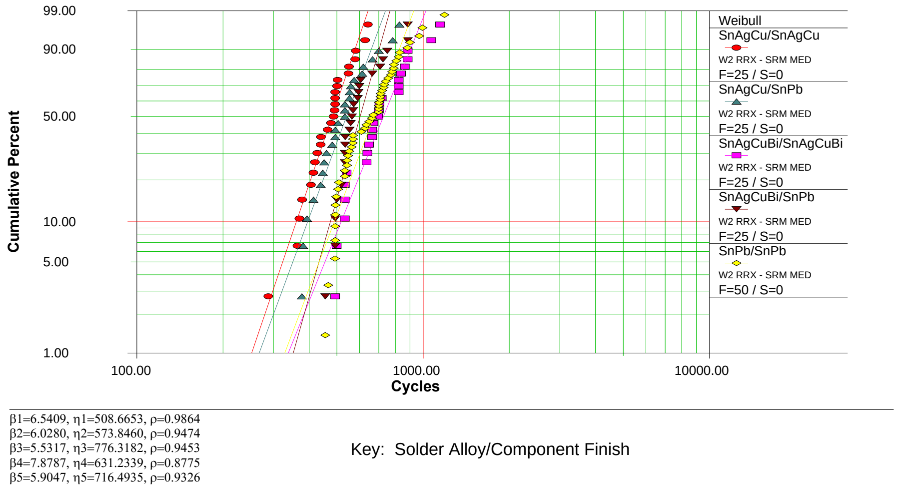
App Fig 12 BGA-225 SAC-SnPb less outlier test results for the "Manufactured" test vehicles (170°C Tg)



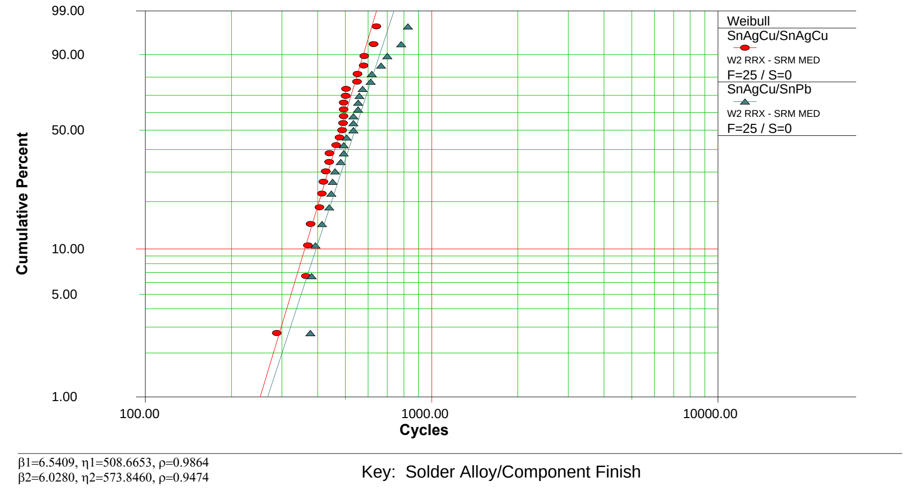
App Fig 13 BGA-225 SAC-SnPb test results for the "Manufactured" test vehicles (170°C Tg)



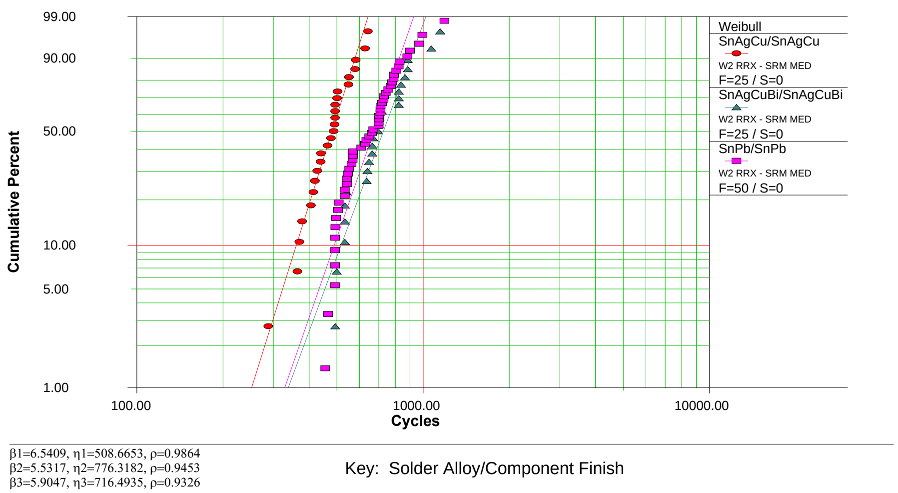
App Fig 14 BGA-225 SnPb test results for the "Manufactured" test vehicles (170°C Tg)



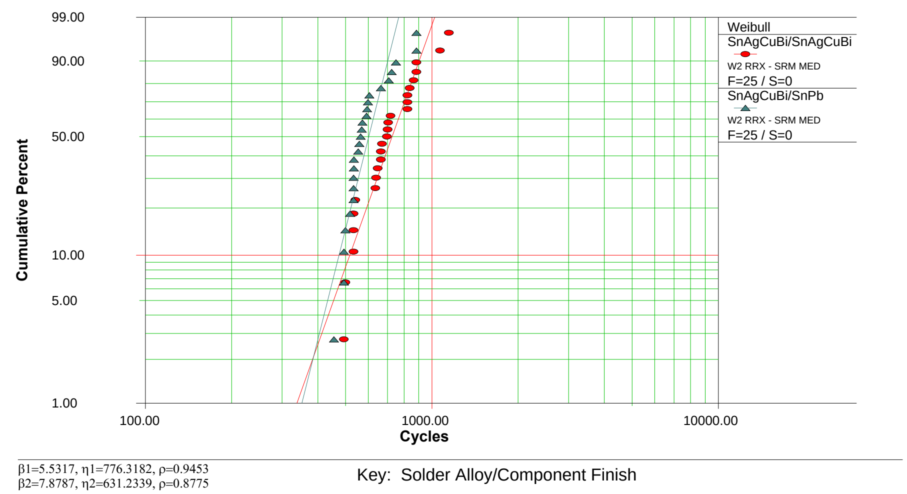
App Fig 15 CLCC-20 all combinations test results for the "Manufactured" test vehicles (170°C Tg)



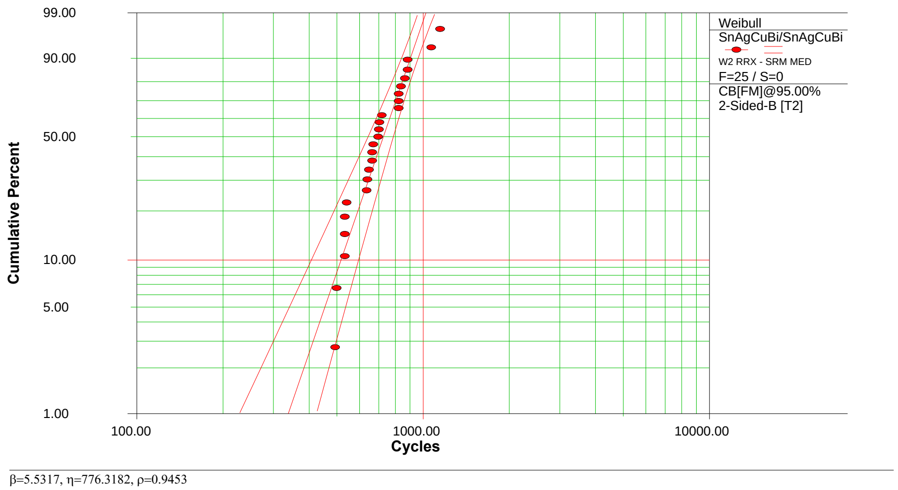
App Fig 17 CLCC-20 SAC test results for the "Manufactured" test vehicles (170°C Tg)



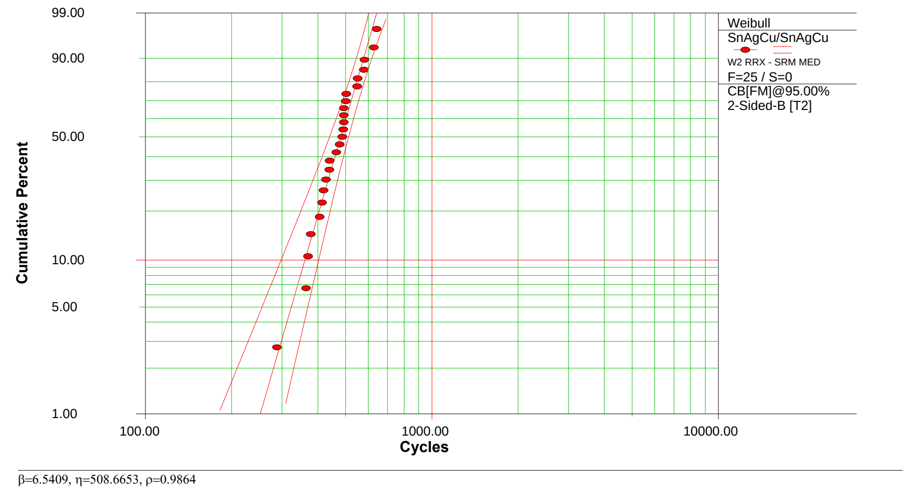
App Fig 16 CLCC-20 Pbfree versus SnPb test results comparison for the "Manufactured" test vehicles (170°C Tg)



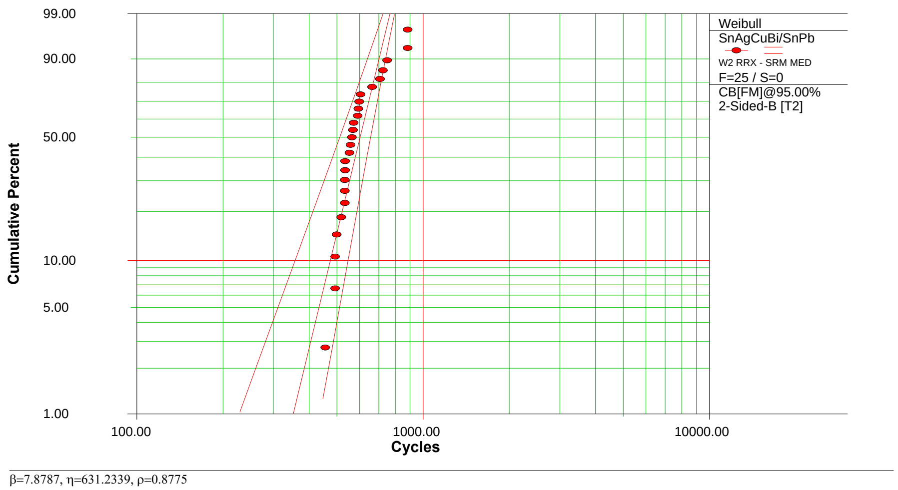
App Fig 18 CLCC-20 SACB test results for the "Manufactured" test vehicles (170°C Tg)



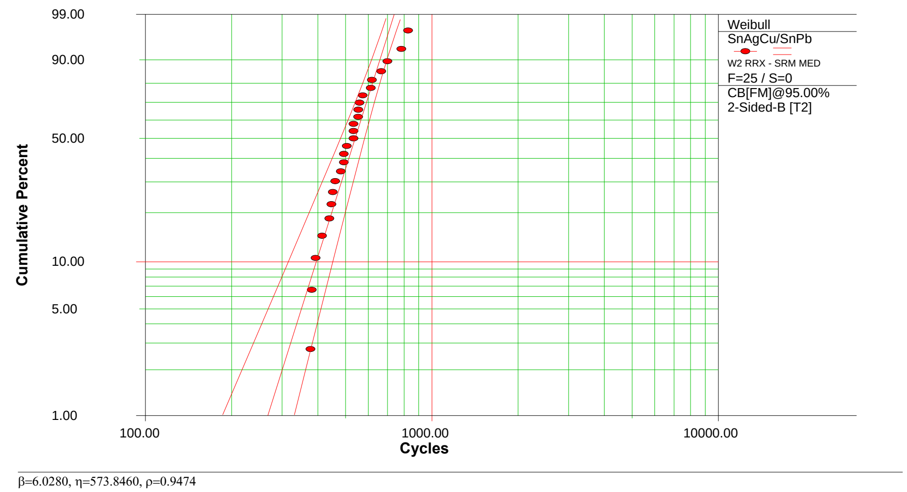
App Fig 19 CLCC-20 SACB-SACB test results for the "Manufactured" test vehicles (170°C Tg)



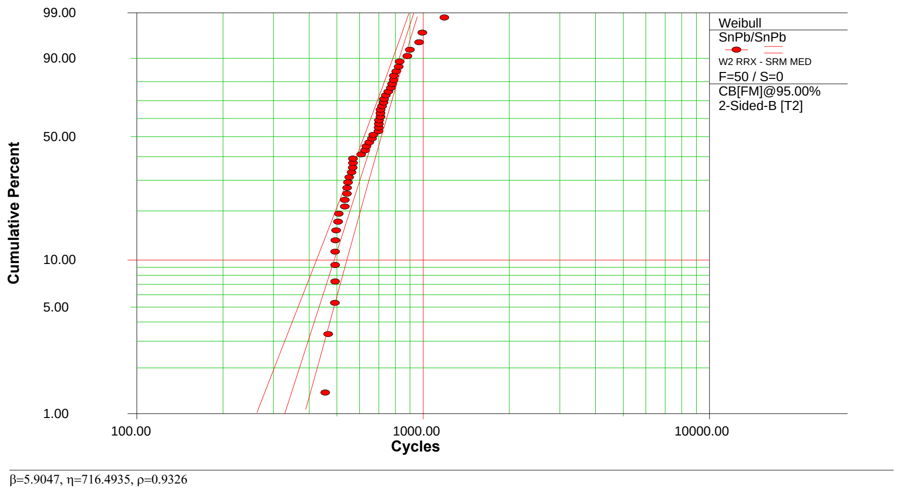
App Fig 21 CLCC-20 SAC-SAC test results for the "Manufactured" test vehicles (170°C Tg)



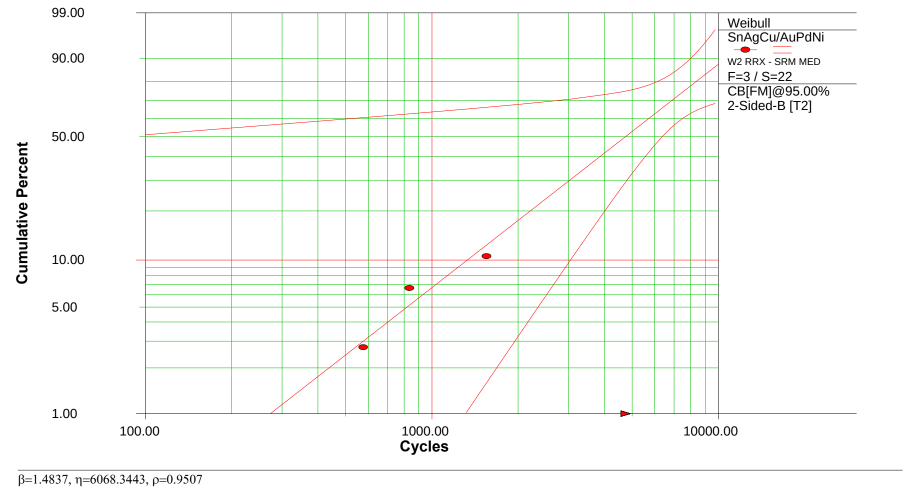
App Fig 20 CLCC-20 SACB-SnPb test results for the "Manufactured" test vehicles (170°C Tg)



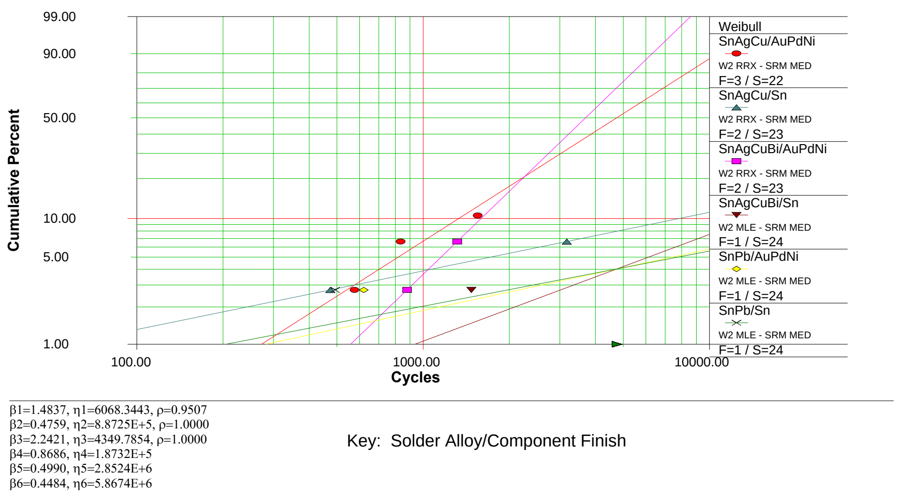
App Fig 22 CLCC-20 SAC-SnPb test results for the "Manufactured" test vehicles (170°C Tg)



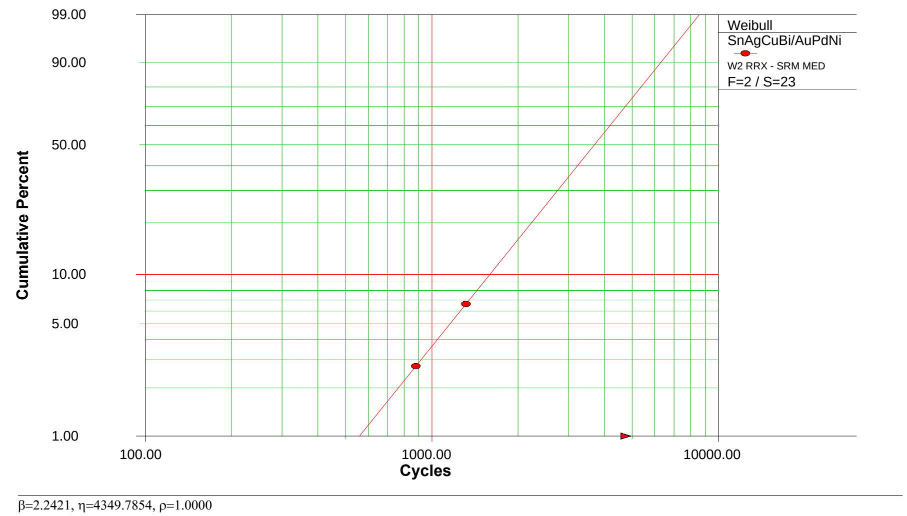
App Fig 23 CLCC-20 SnPb-SnPb test results for the "Manufactured" test vehicles (170°C Tg)



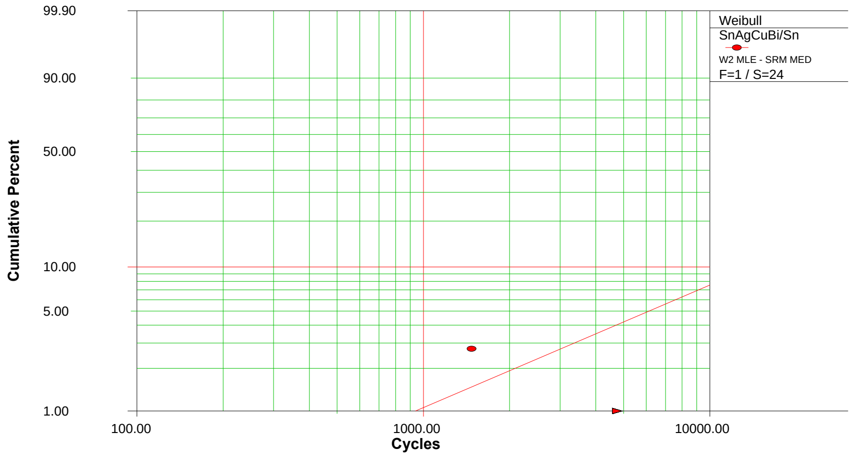
App Fig 25 DIP-20 SAC - AuPdNi test results for the "Manufactured" test vehicles (170°C Tg)



App Fig 24 DIP-20 all combinations test results for the "Manufactured" test vehicles (170°C Tg)

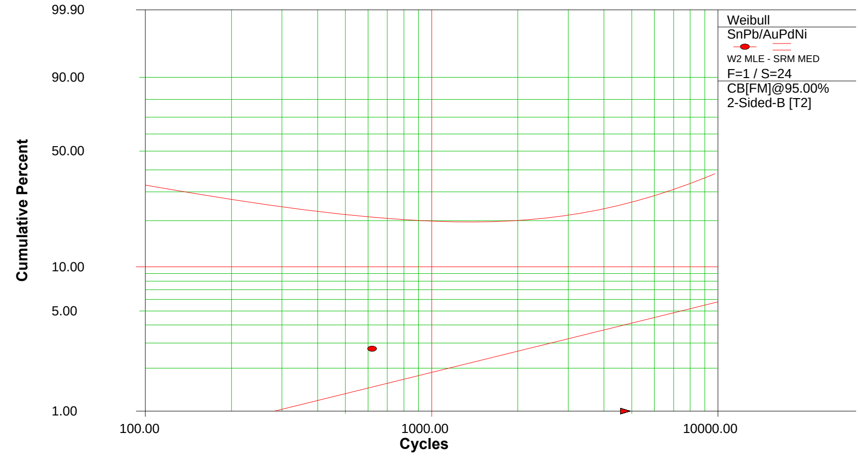


App Fig 26 DIP-20 SACB-AuPdNi test results for the "Manufactured" test vehicles (170°C Tg)



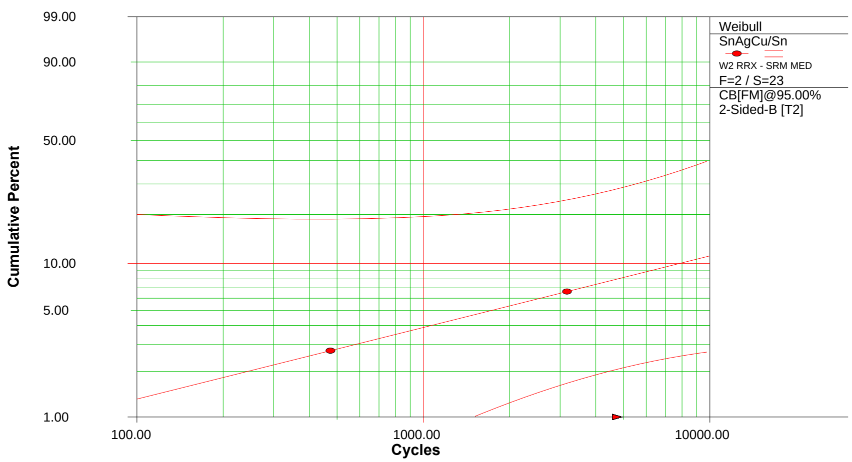
β=0.8686, η=1.8732E+5

App Fig 27 DIP-20 SACB-Sn test results for the "Manufactured" test vehicles (170°C Tg)



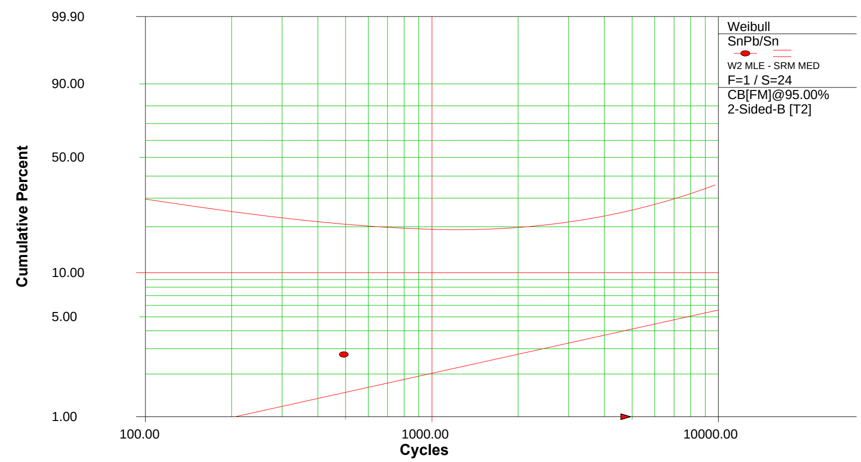
β=0.4990, η=2.8524E+6

App Fig 29 DIP-20 SnPb - AuPdNi test results for the "Manufactured" test vehicles (170°C Tg)



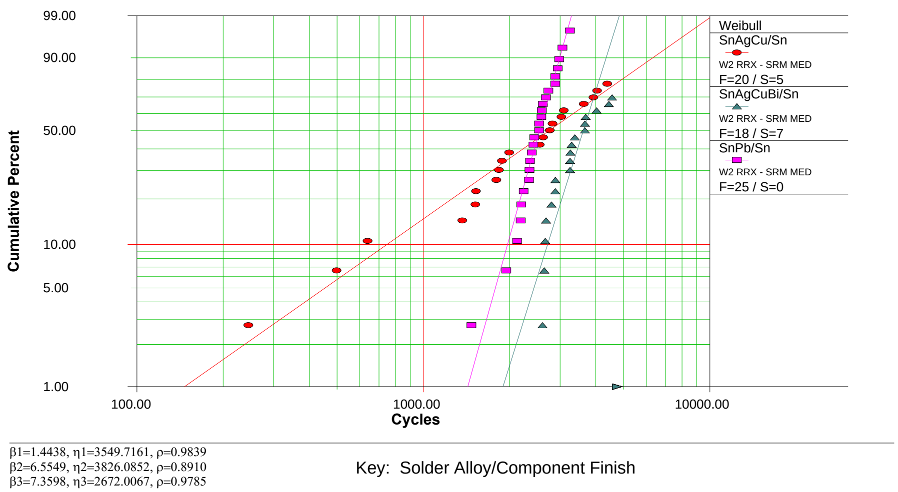
β=0.4759, η=8.8725E+5, ρ=1.0000

App Fig 28 DIP-20 SAC-Sn test results for the "Manufactured" test vehicles (170°C Tg)

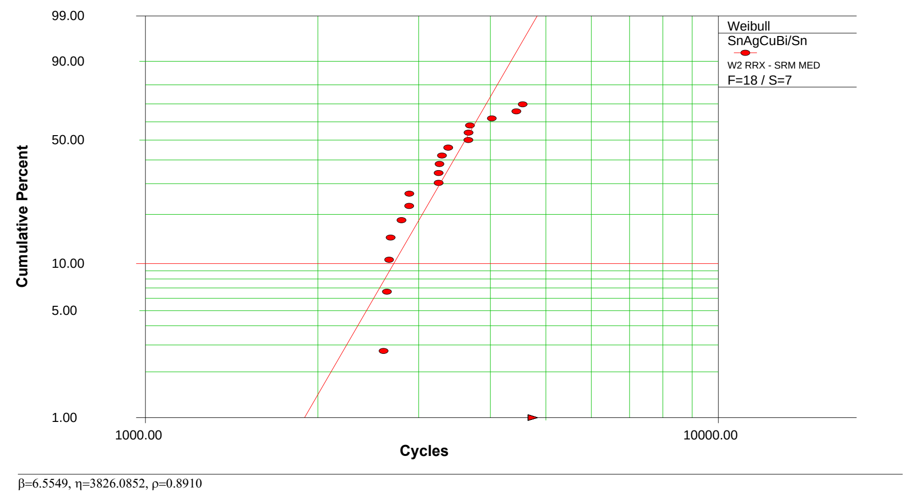


β=0.4484, η=5.8674E+6

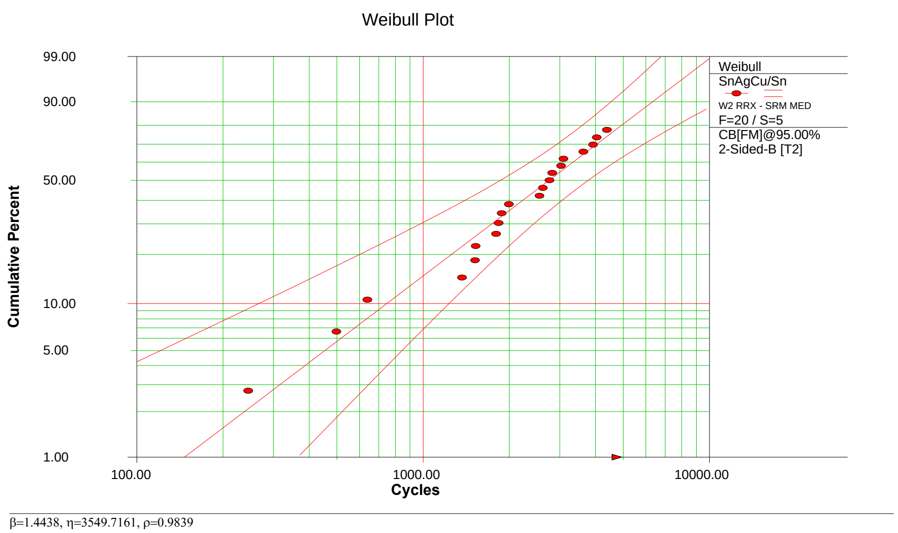
App Fig 30 DIP-20 SnPb – Sn test results for the "Manufactured" test vehicles (170°C Tg)



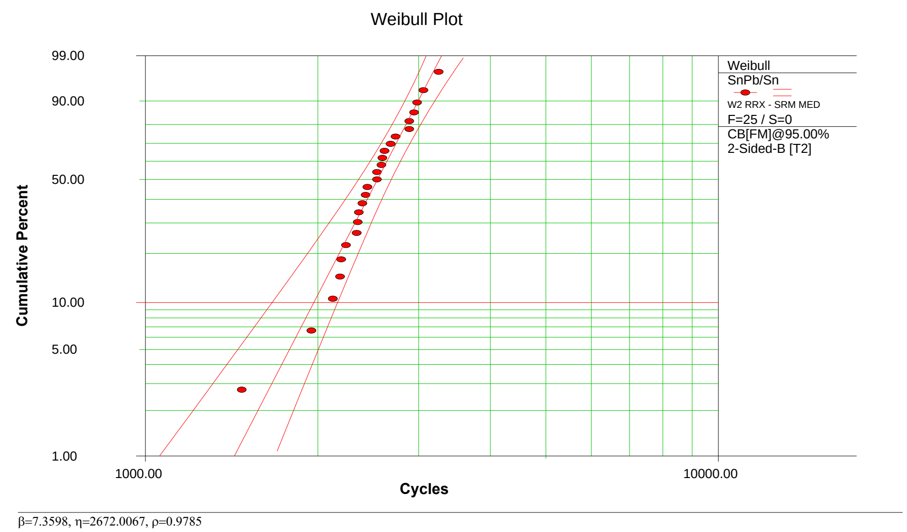
App Fig 31 TQFP-144 all combinations test results for the "Manufactured" test vehicles (170°C Tg)



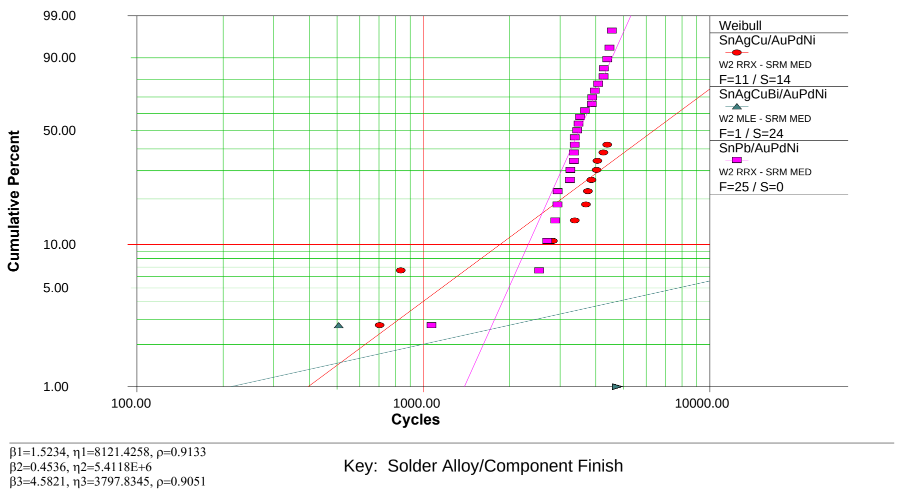
App Fig 33 TQFP-144 SACB test results for the "Manufactured" test vehicles (170°C Tg)



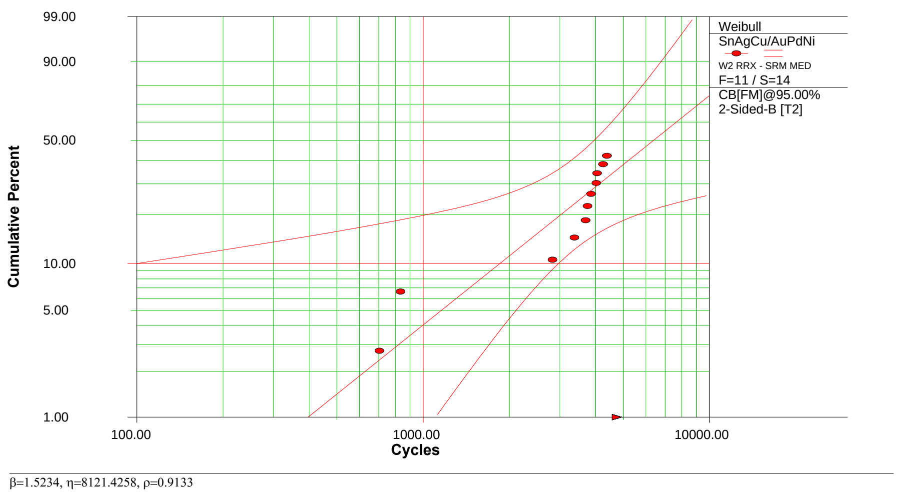
App Fig 32 TQFP-144 SAC test results for the "Manufactured" test vehicles (170°C Tg)



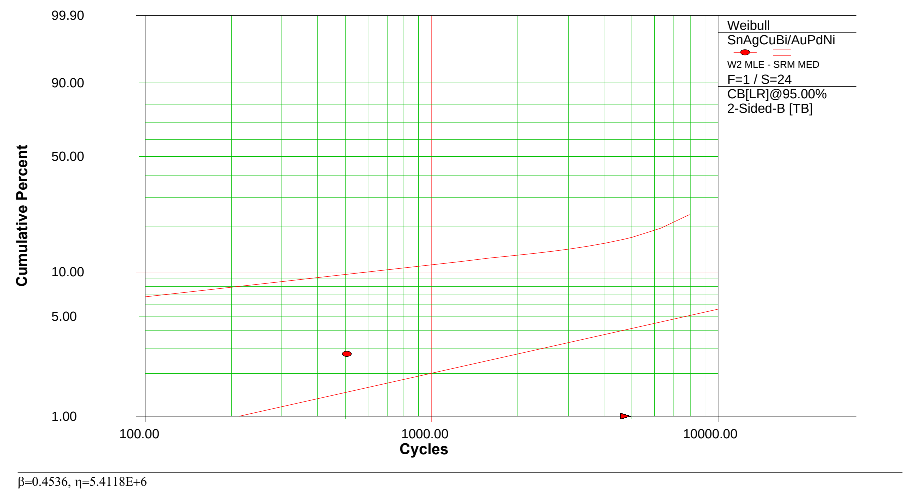
App Fig 34 TQFP-144 SnPb test results for the "Manufactured" test vehicles (170°C Tg)



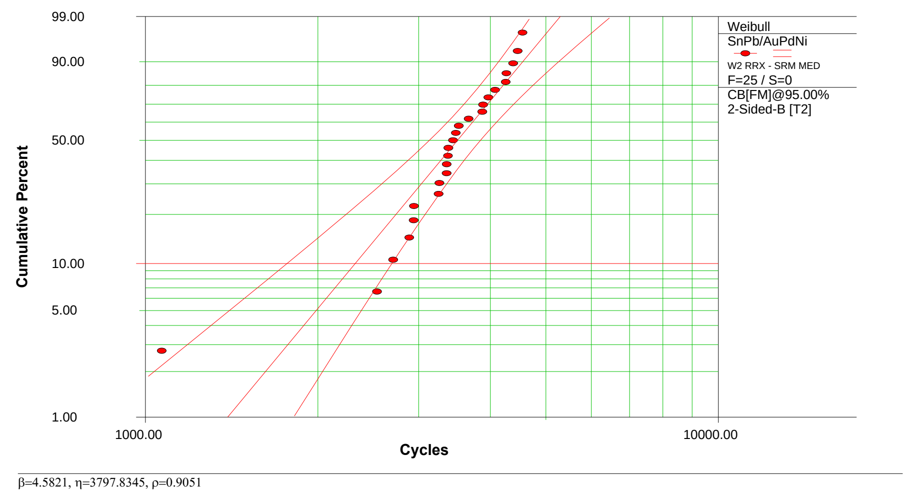
App Fig 35 TQFP-208 all combinations test results for the "Manufactured" test vehicles (170°C Tg)



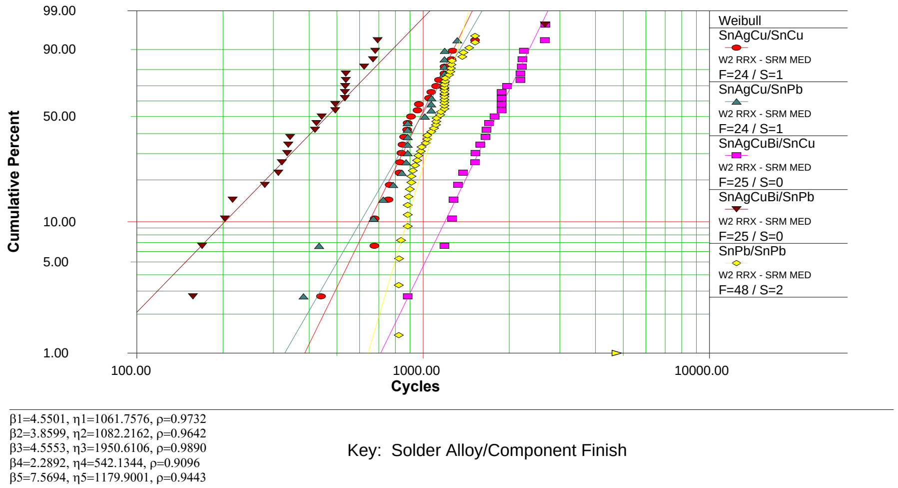
App Fig 36 TQFP-208 SAC test results for the "Manufactured" test vehicles (170°C Tg)



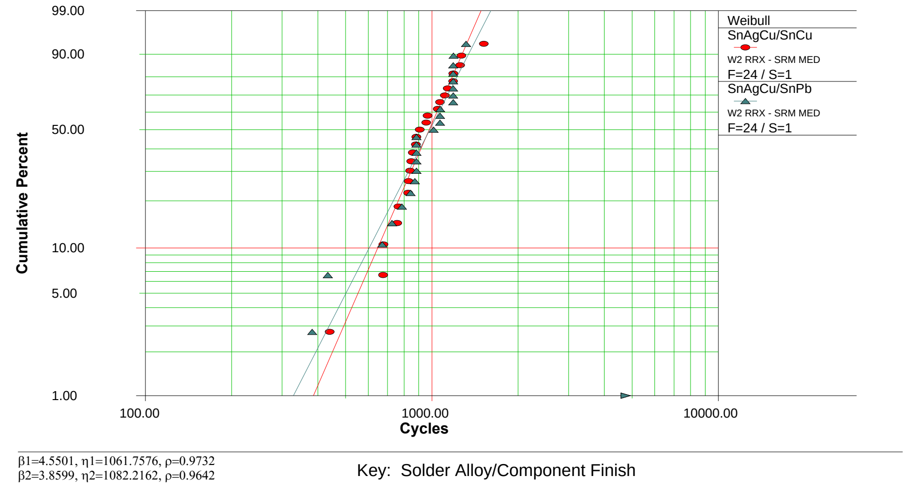
App Fig 37 TQFP-208 SACB test results for the "Manufactured" test vehicles (170°C Tg)



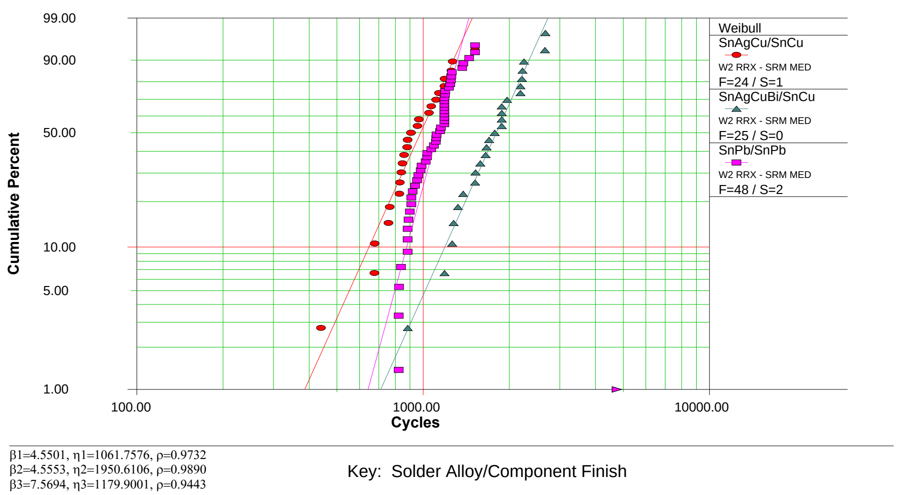
App Fig 38 TQFP-208 SnPb test results for the "Manufactured" test vehicles (170°C Tg)



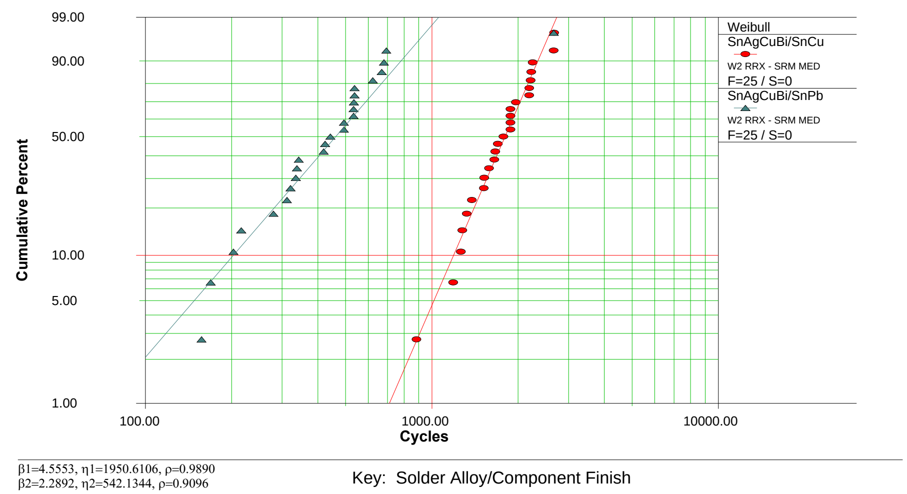
App Fig 39 TSOP-50 all combinations test results for the "Manufactured" test vehicles (170°C Tg)



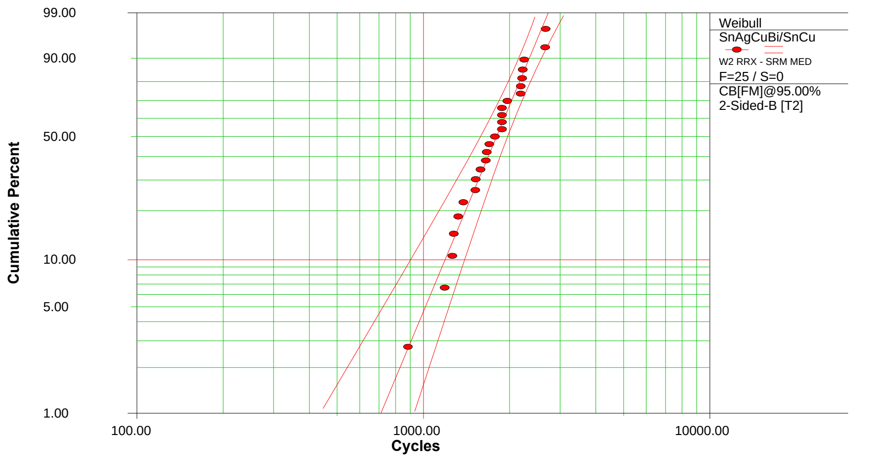
App Fig 41 TSOP-50 SAC test results for the "Manufactured" test vehicles (170°C Tg)



App Fig 40 TSOP-50 Pbfree versus SnPb test results comparison for the "Manufactured" test vehicles (170°C Tg)

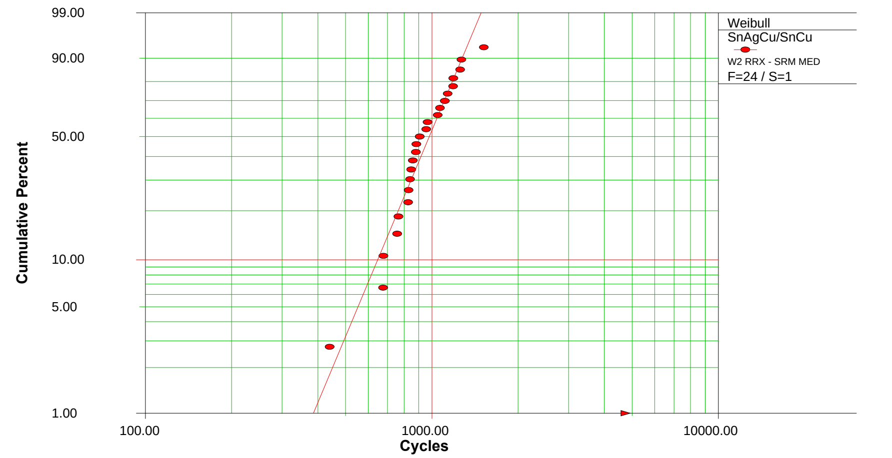


App Fig 42 TSOP-50 SACB test results for the "Manufactured" test vehicles (170°C Tg)



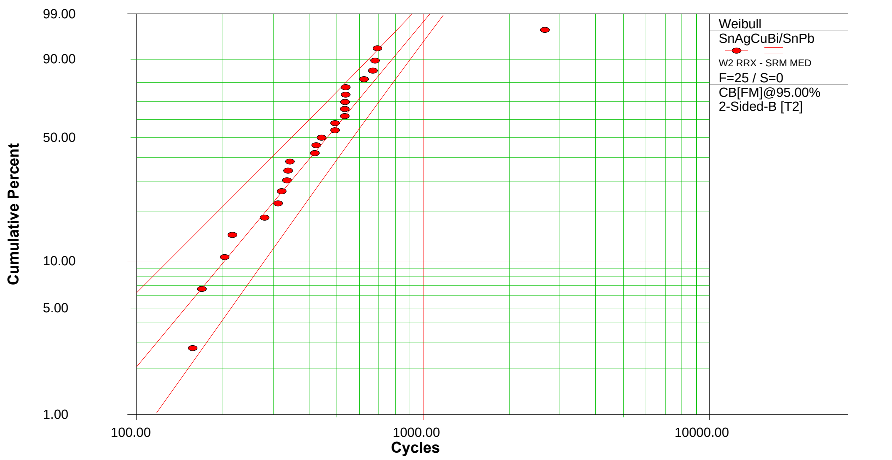
β=4.5553, η=1950.6106, ρ=0.9890

App Fig 43 TSOP-50 SACB-SnCu test results for the "Manufactured" test vehicles (170°C Tg)



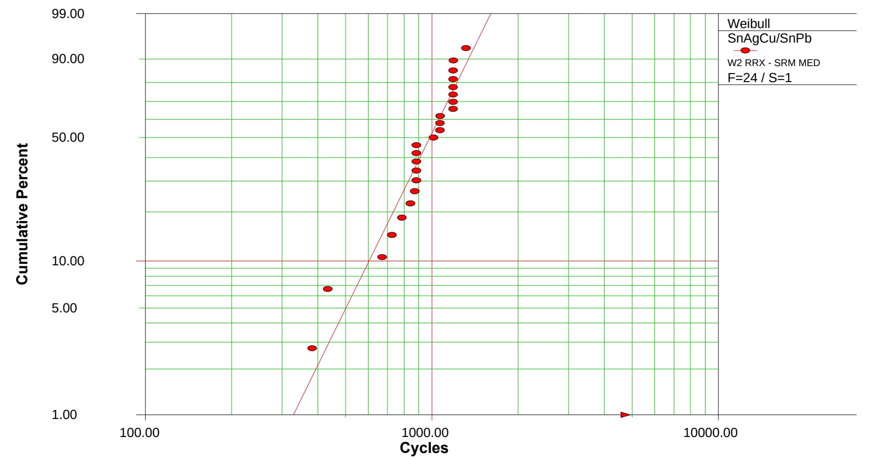
β=4.5501, η=1061.7576, ρ=0.9732

App Fig 45 TSOP-50 SAC-SnCu test results for the "Manufactured" test vehicles (170°C Tg)



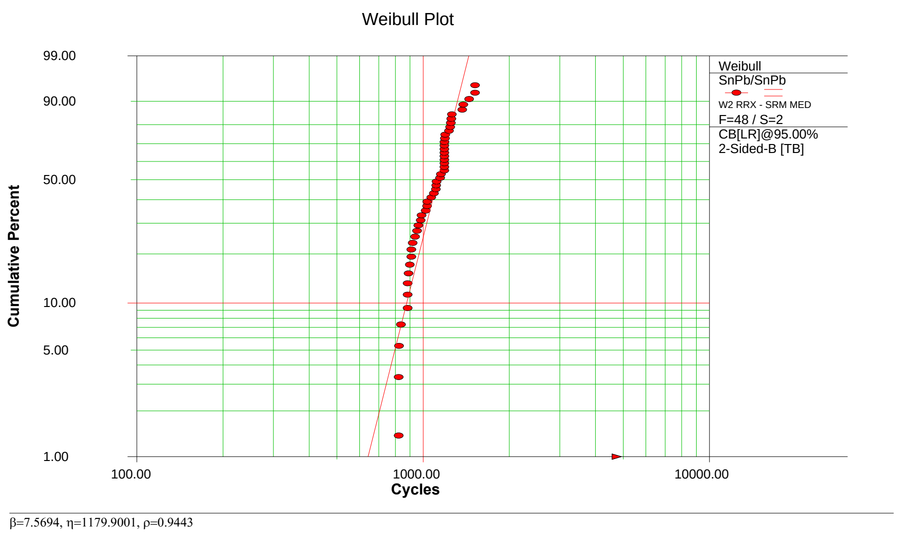
β=2.2892, η=542.1344, ρ=0.9096

App Fig 44 TSOP-50 SACB-SnPb test results for the "Manufactured" test vehicles (170°C Tg)



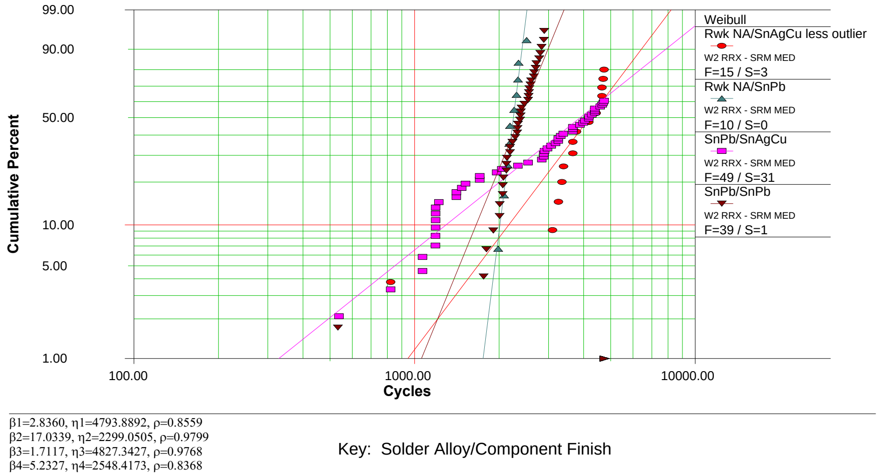
β=3.8599, η=1082.2162, ρ=0.9642

App Fig 46 TSOP-50 SAC-SnPb test results for the "Manufactured" test vehicles (170°C Tg)

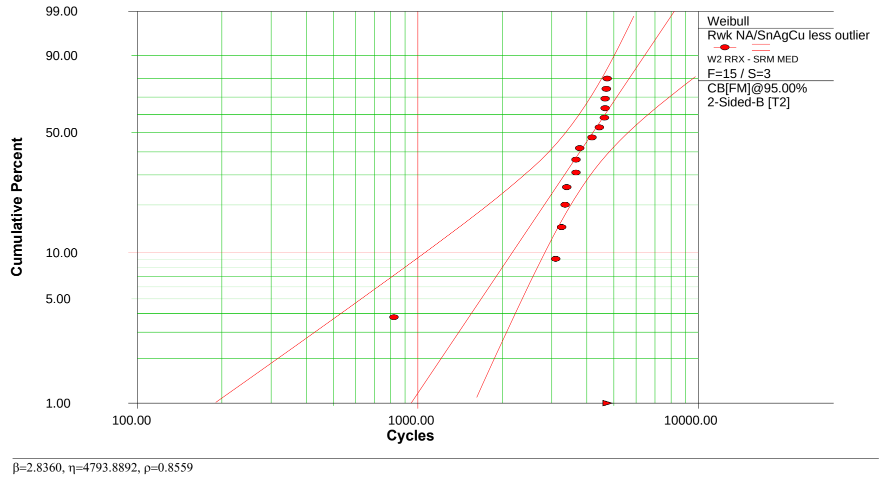


App Fig 47 TSOP-50 SnPb - SnPb test results for “Manufactured” test vehicles (170ºC Tg)

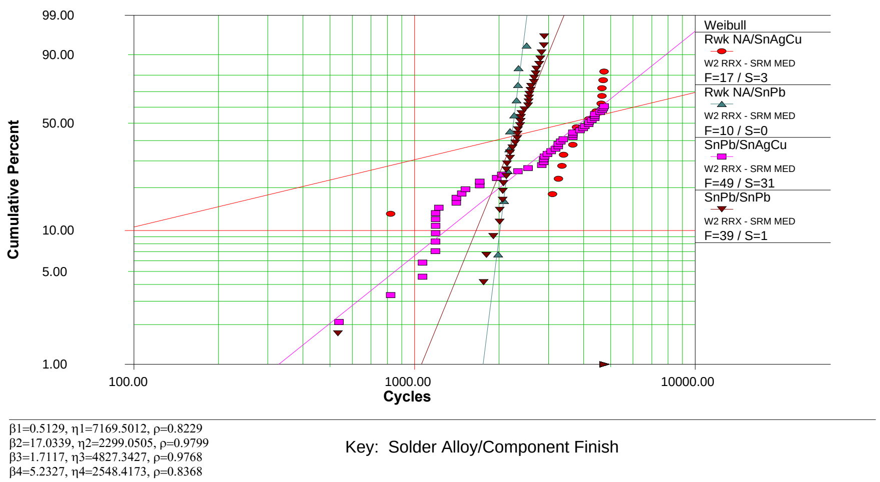
Appendix F Weibull Charts "Reworked" Test Vehicles



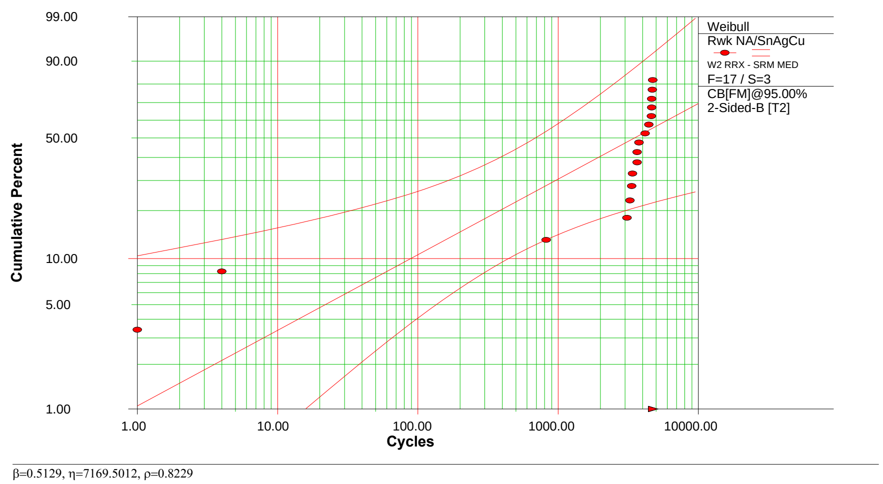
App Fig 48 BGA-225 combinations less outlier test results for the legacy ("Rework") test vehicles (140°C Tg)



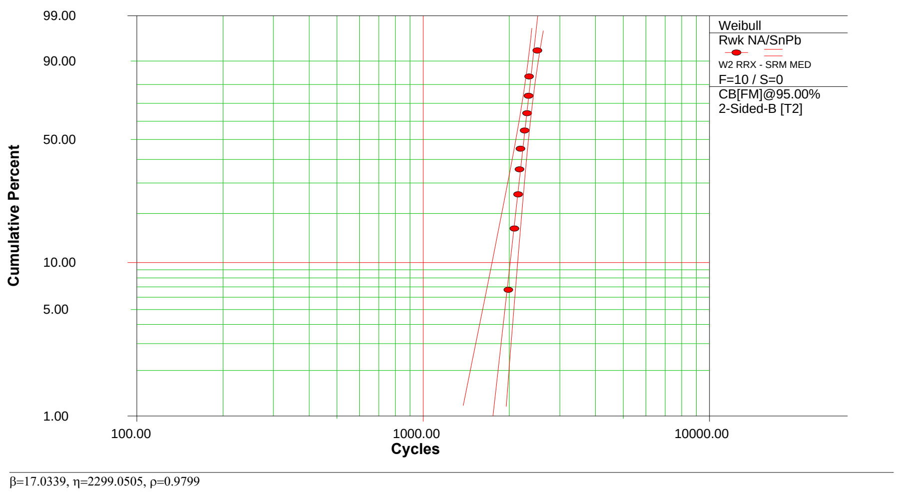
App Fig 50 BGA-225 Reworked NA/SAC less outlier test results for the legacy ("Rework") test vehicles (140°C Tg)



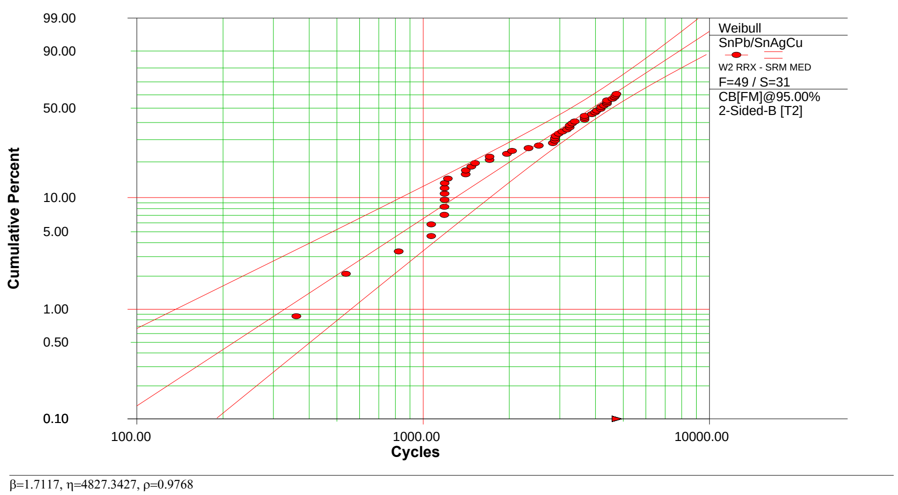
App Fig 49 BGA-225 combinations test results for the legacy ("Rework") test vehicles (140°C Tg)



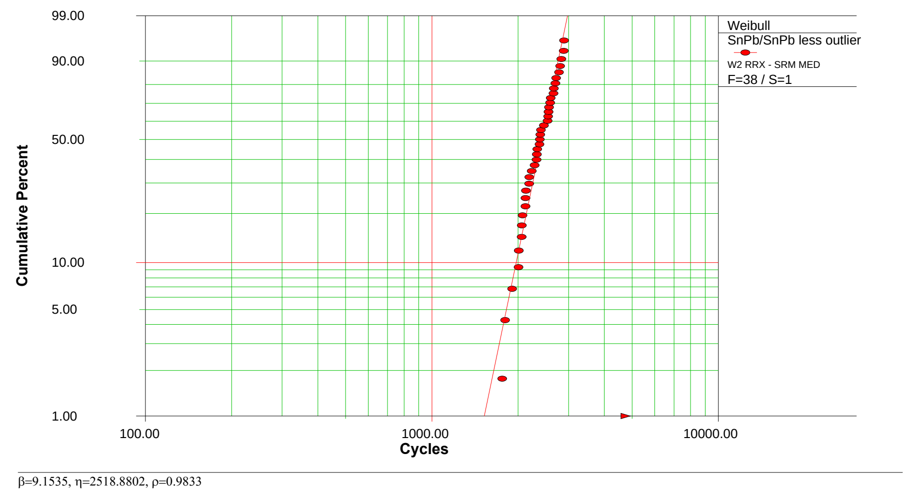
App Fig 51 BGA-225 Reworked NA/SAC test results for the legacy ("Rework") test vehicles (140°C Tg)



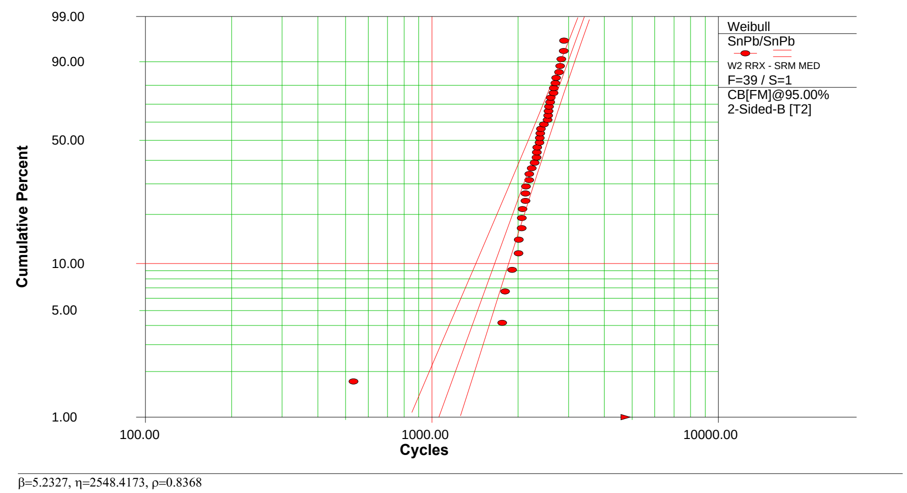
App Fig 52 BGA-225 Reworked NA/SnPb test results for the legacy ("Rework") test vehicles (140°C Tg)



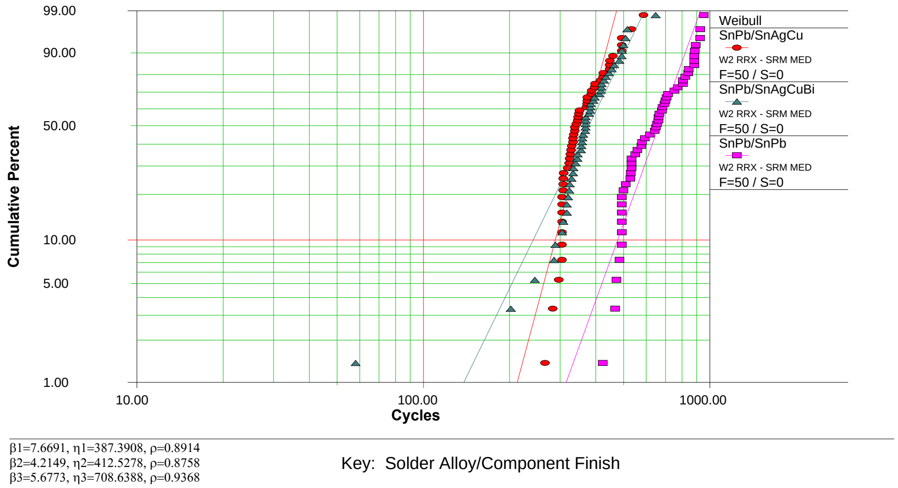
App Fig 53 BGA-225 SnPb-SAC test results for the legacy ("Rework") test vehicles (140°C Tg)



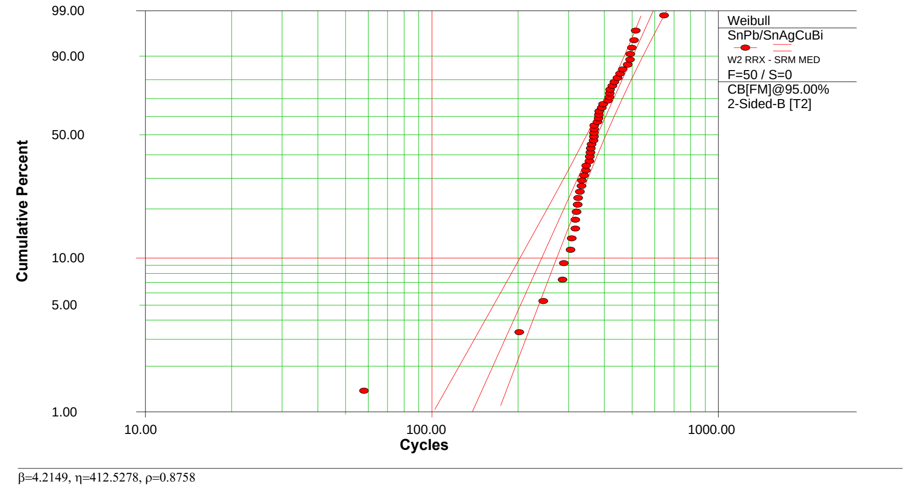
App Fig 54 BGA-225 SnPb-SnPb less outlier test results for the legacy ("Rework") test vehicles (140°C Tg)



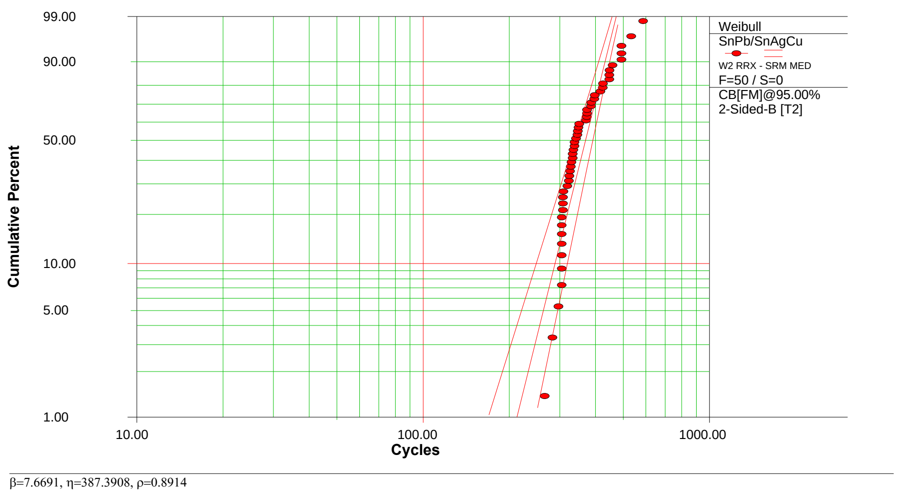
App Fig 55 BGA-225 SnPb-SnPb test results for the legacy ("Rework") test vehicles (140°C Tg)



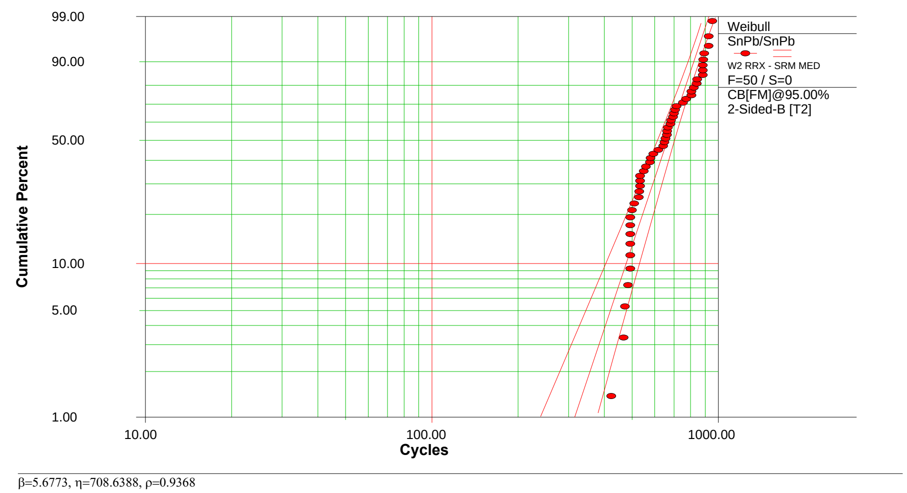
App Fig 56 CLCC-20 all combinations test results for the legacy ("Rework") test vehicles (140°C Tg)



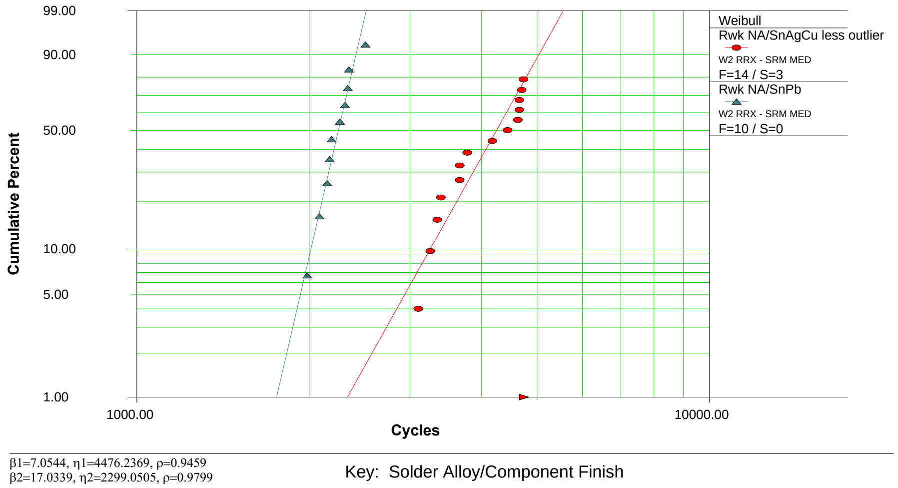
App Fig 58 CLCC-20 SnPb-SACB test results for the legacy ("Rework") test vehicles (140°C Tg)



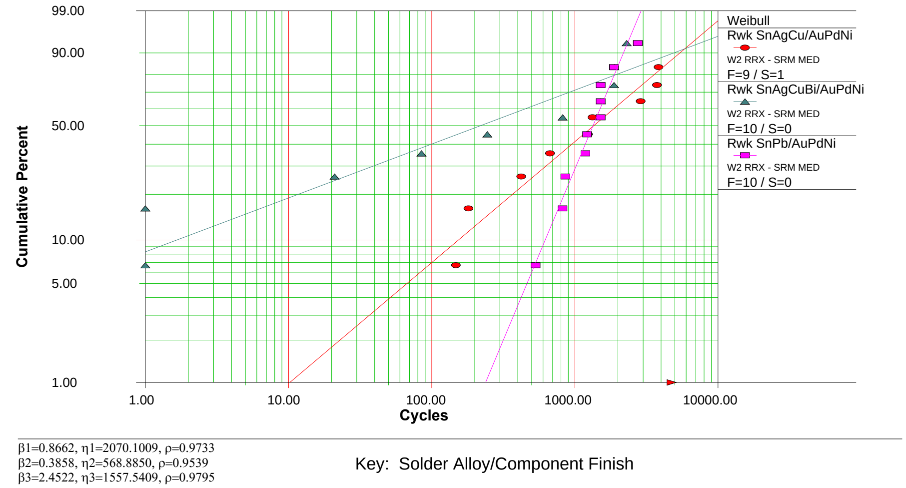
App Fig 57 CLCC-20 SnPb-SAC test results for the legacy ("Rework") test vehicles (140°C Tg)



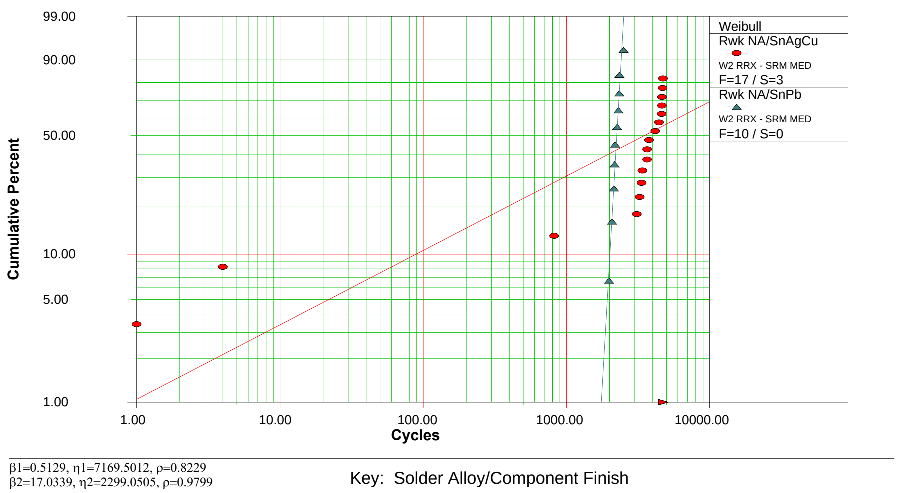
App Fig 59 CLCC-20 SnPb-SnPb test results for the legacy ("Rework") test vehicles (140°C Tg)



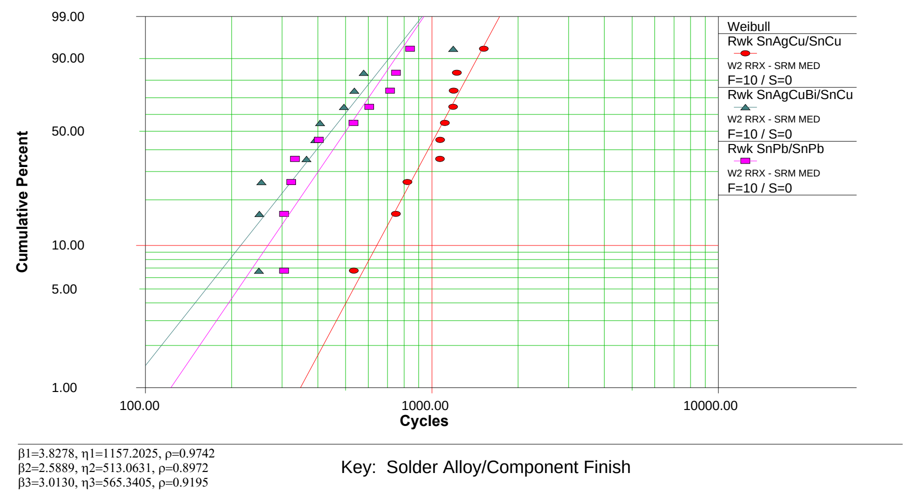
App Fig 60 BGA-225 Reworked less outlier test results for the legacy (“Rework”) test vehicles (140°C Tg)



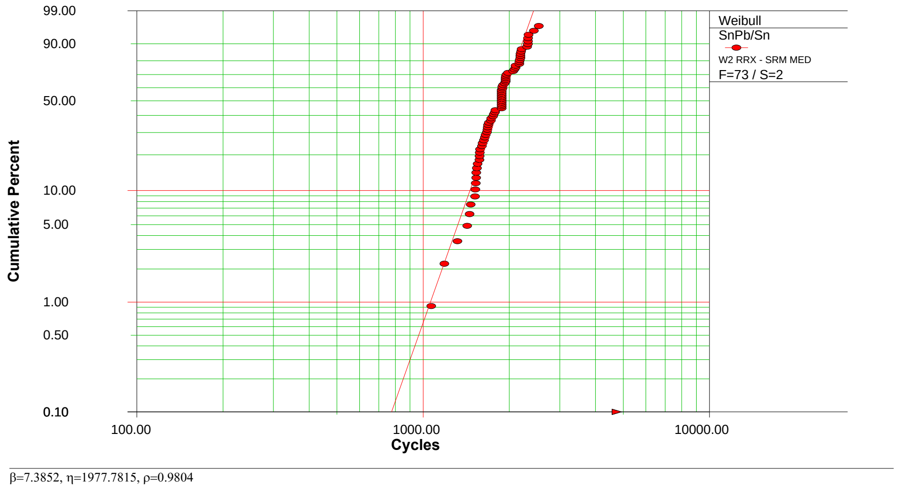
App Fig 62 TQFP-208 Reworked test results for the legacy (“Rework”) test vehicles (140°C Tg)



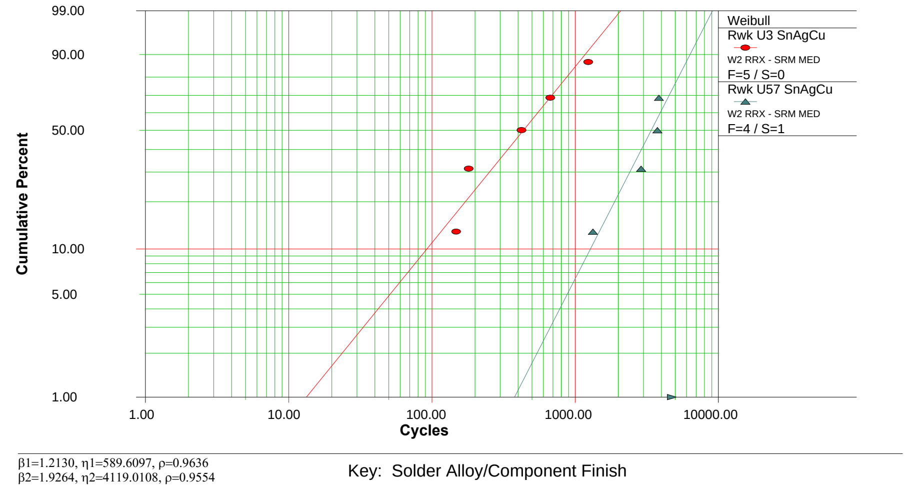
App Fig 61 BGA-225 Reworked test results for the legacy (“Rework”) test vehicles (140°C Tg)



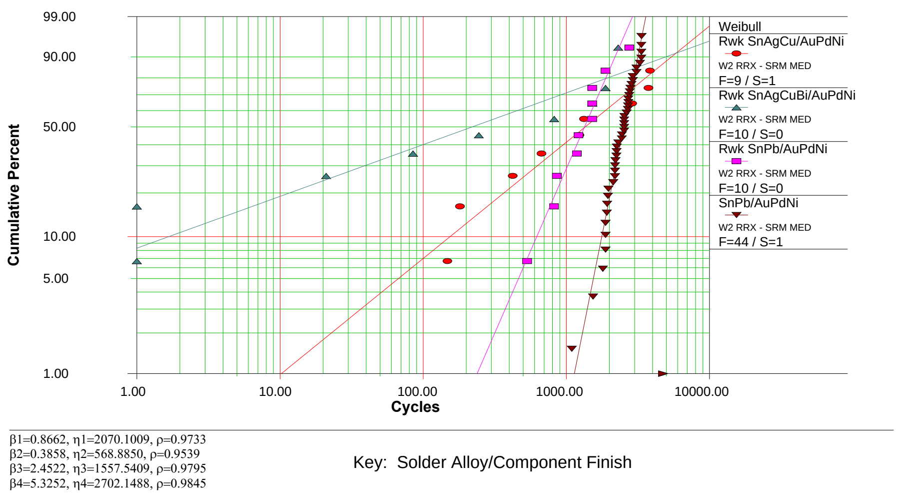
App Fig 63 TSOP-50 Reworked test results for the legacy (“Rework”) test vehicles (140°C Tg)



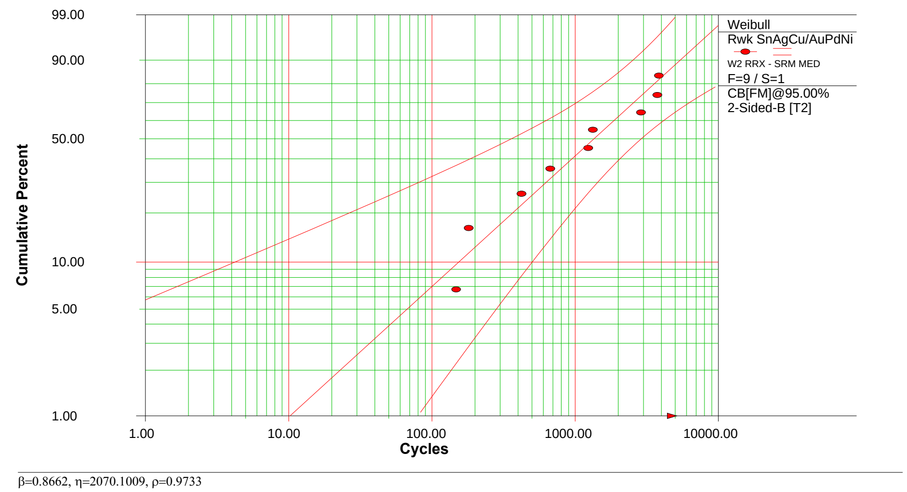
App Fig 64 TQFP-144 test results for the legacy (“Rework”) test vehicles (140°C Tg)



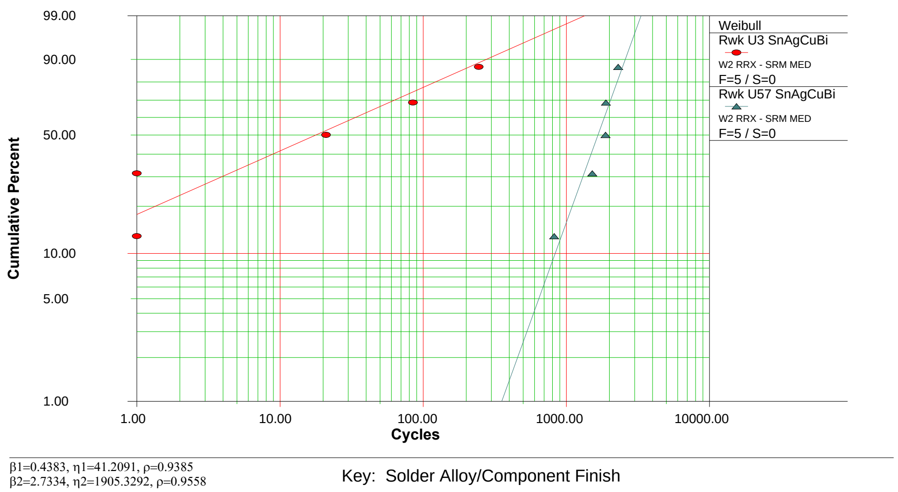
App Fig 66 TQFP-208 Reworked SAC U3 versus U57 test results comparison for the legacy (“Rework”) test vehicles (140°C)



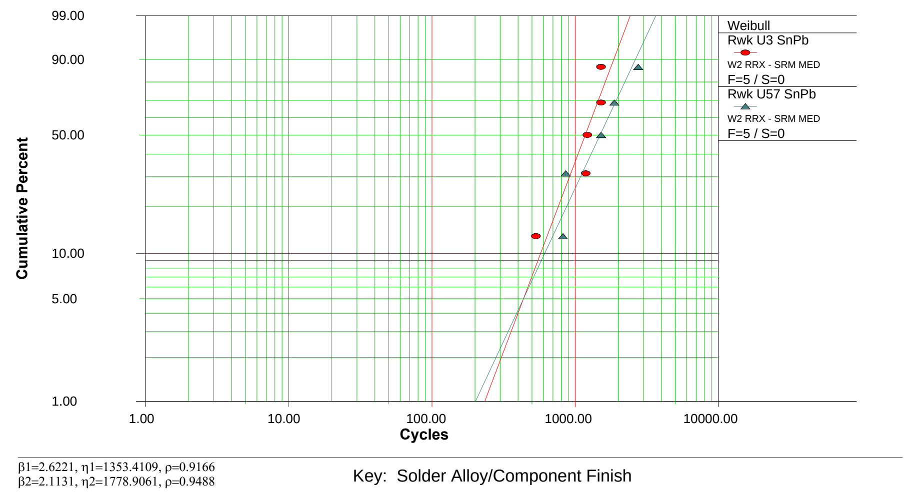
App Fig 65 TQFP-208 all combinations test results for the legacy (“Rework”) test vehicles (140°C Tg)



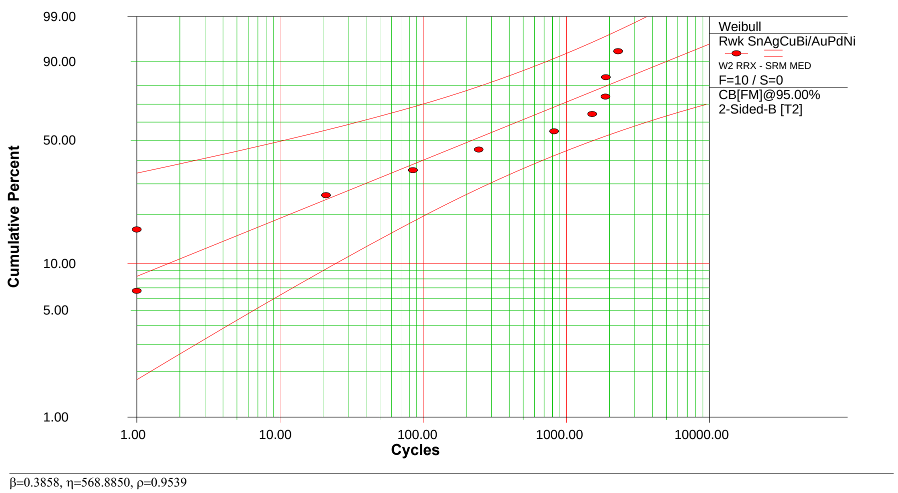
App Fig 67 TQFP-208 Reworked SAC test results for the legacy (“Rework”) test vehicles (140°C Tg)



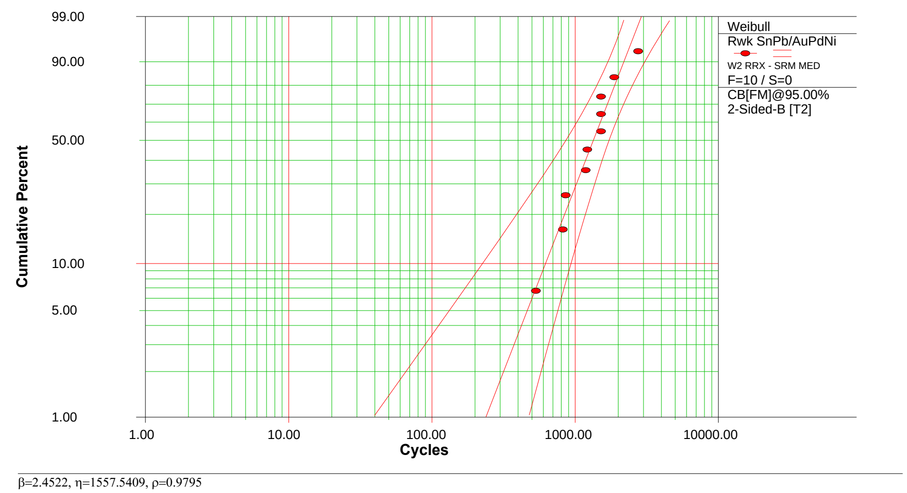
App Fig 68 TQFP-208 Reworked SACB U3 versus U57 test results comparison for the legacy ("Rework") test vehicles (140°C Tg)



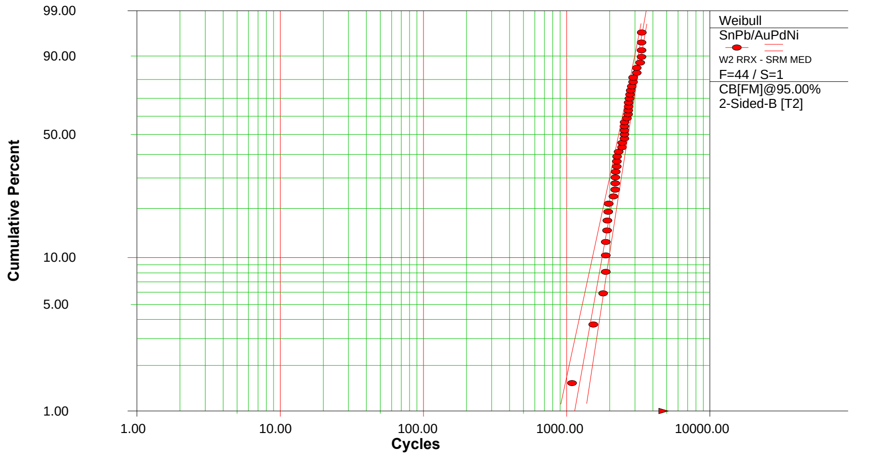
App Fig 70 TQFP-208 Reworked SnPb U3 versus U57 test results comparison for the legacy ("Rework") test vehicles (140°C Tg)



App Fig 69 TQFP-208 Reworked SACB test results for the legacy ("Rework") test vehicles (140°C Tg)

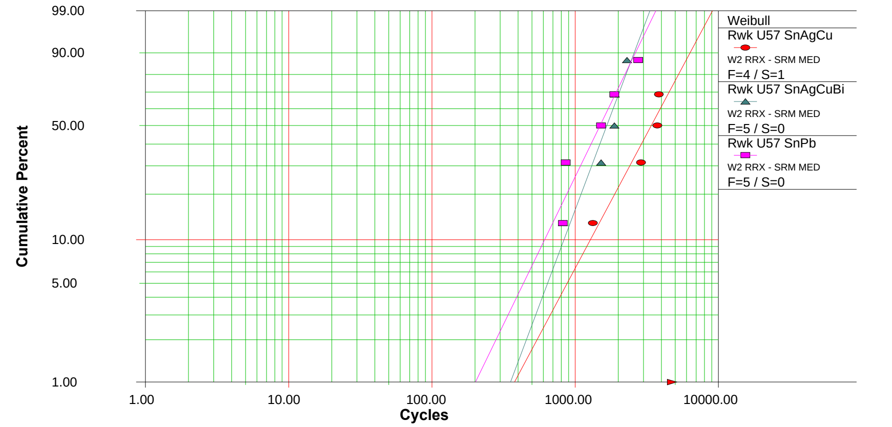


App Fig 71 TQFP-208 Reworked SnPb test results for the legacy ("Rework") test vehicles (140°C Tg)



β=5.3252, η=2702.1488, ρ=0.9845

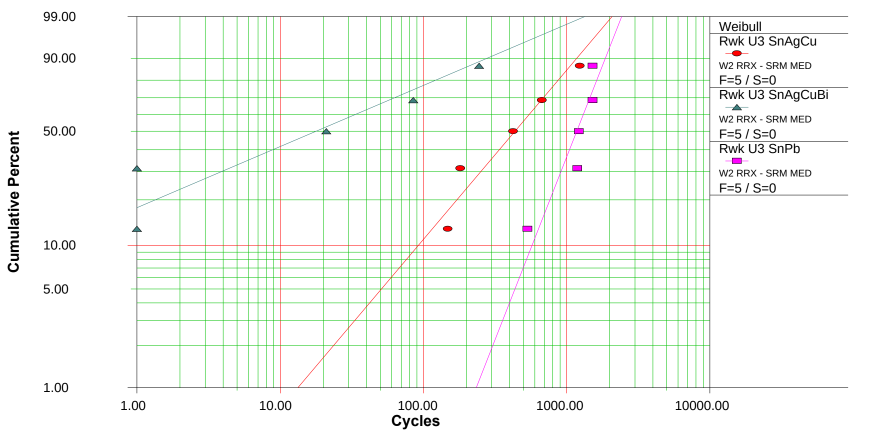
App Fig 72 TQFP-208 SnPb test results for the legacy ("Rework") test vehicles (140°C Tg)



β1=1.9264, η1=4119.0108, ρ=0.9554
β2=2.7334, η2=1905.3292, ρ=0.9558
β3=2.1131, η3=1778.9061, ρ=0.9488

Key: Solder Alloy/Component Finish

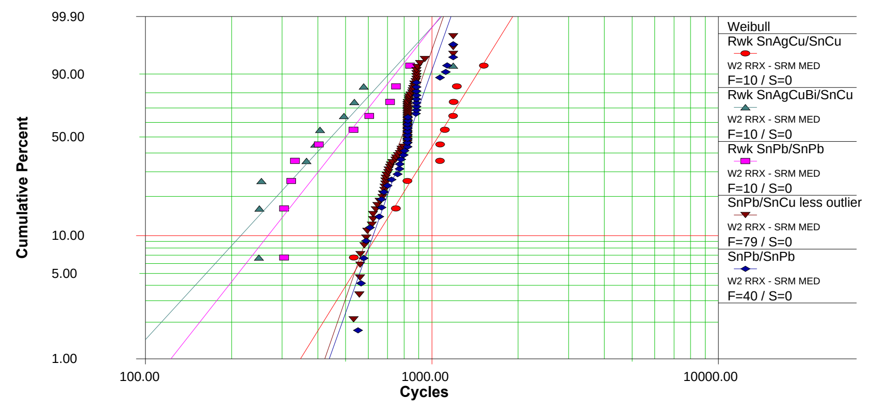
App Fig 74 TQFP-208 Reworked U57 test results comparison for the legacy ("Rework") test vehicles (140°C Tg)



β1=1.2130, η1=589.6097, ρ=0.9636
β2=0.4383, η2=41.2091, ρ=0.9385
β3=2.6221, η3=1353.4109, ρ=0.9166

Key: Solder Alloy/Component Finish

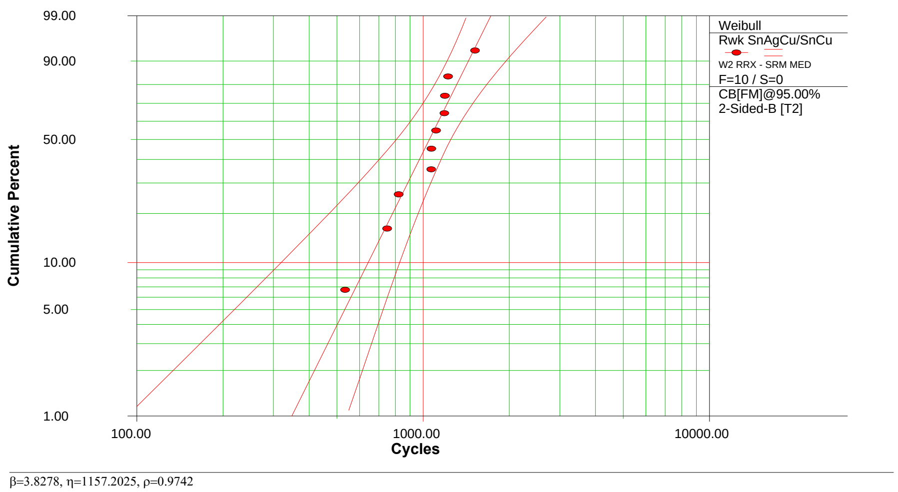
App Fig 73 TQFP-208 Reworked U3 test results comparison for the legacy ("Rework") test vehicles (140°C Tg)



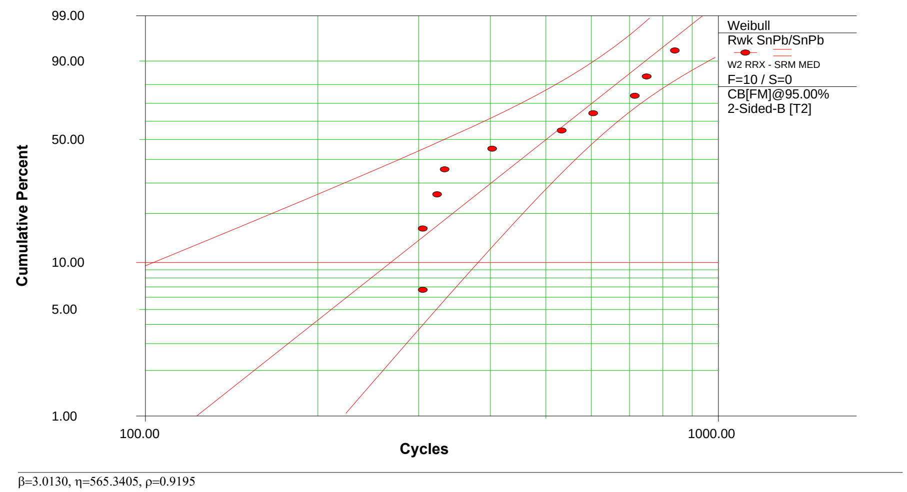
β1=3.8278, η1=1157.2025, ρ=0.9742
β2=2.5889, η2=513.0631, ρ=0.8972
β3=3.0130, η3=565.3405, ρ=0.9195
β4=6.8469, η4=827.4517, ρ=0.9547
β5=6.6749, η5=873.4001, ρ=0.9541

Key: Solder Alloy/Component Finish

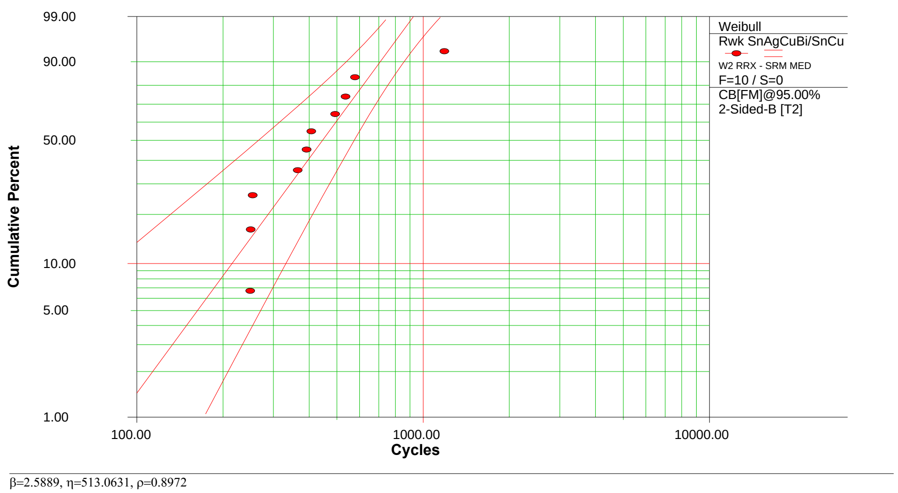
App Fig 75 TSOP-50 all combinations test results comparison for the legacy ("Rework") test vehicles (140°C Tg)



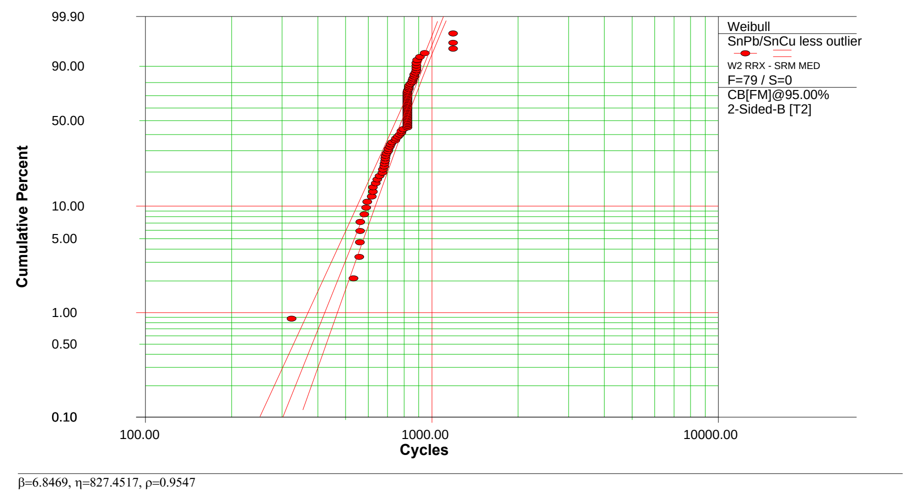
App Fig 76 TSOP-50 Reworked SAC test results for the legacy (“Rework”) test vehicles (140°C Tg)



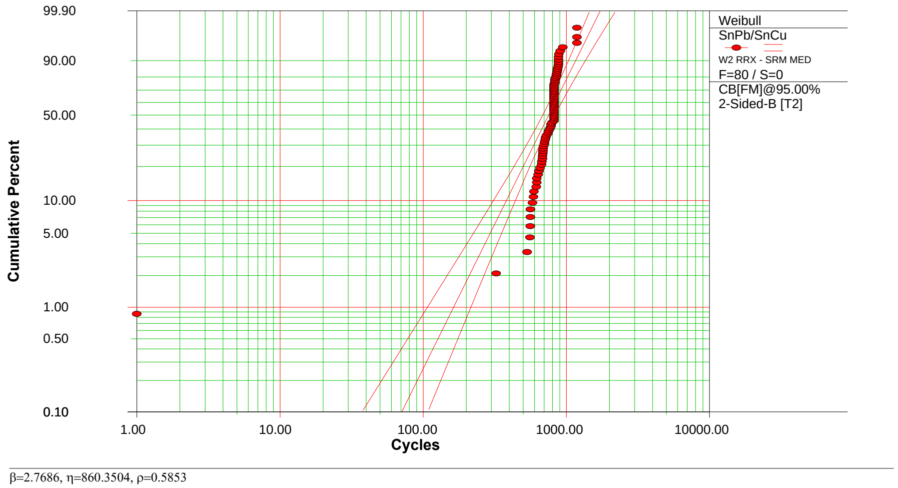
App Fig 78 TSOP-50 Reworked SnPb test results for the legacy (“Rework”) test vehicles (140°C Tg)



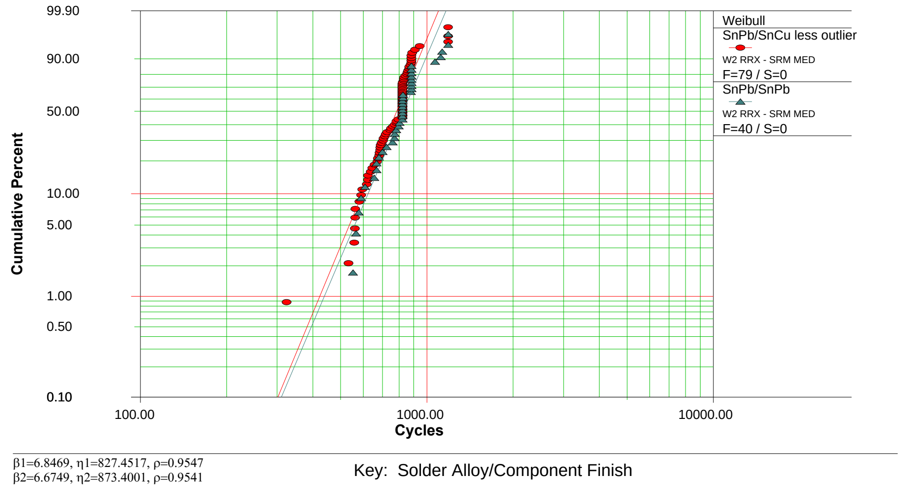
App Fig 77 TSOP-50 Reworked SACB test results for the legacy (“Rework”) test vehicles (140°C Tg)



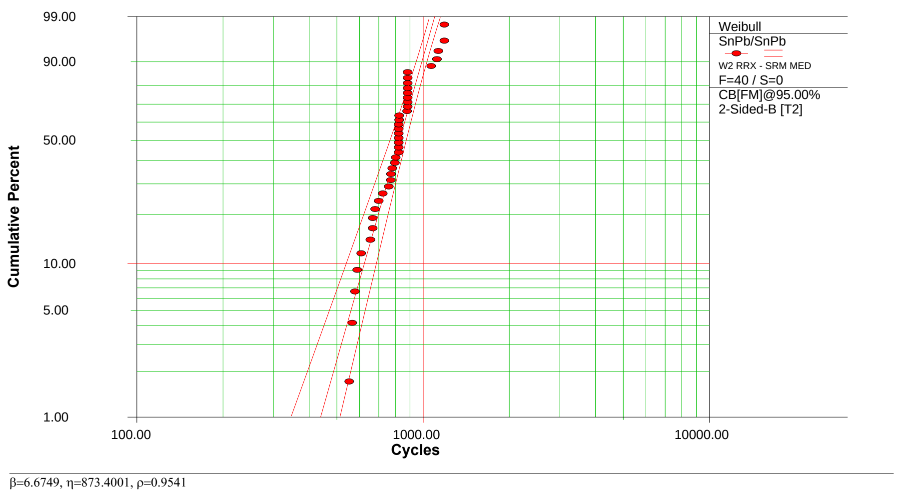
App Fig 79 TSOP-50 SnPb-SnCu less outlier test results for the legacy (“Rework”) test vehicles (140°C Tg)



App Fig 80 TSOP-50 SnPb-SnCu test results for the legacy ("Rework") test vehicles (140°C Tg)

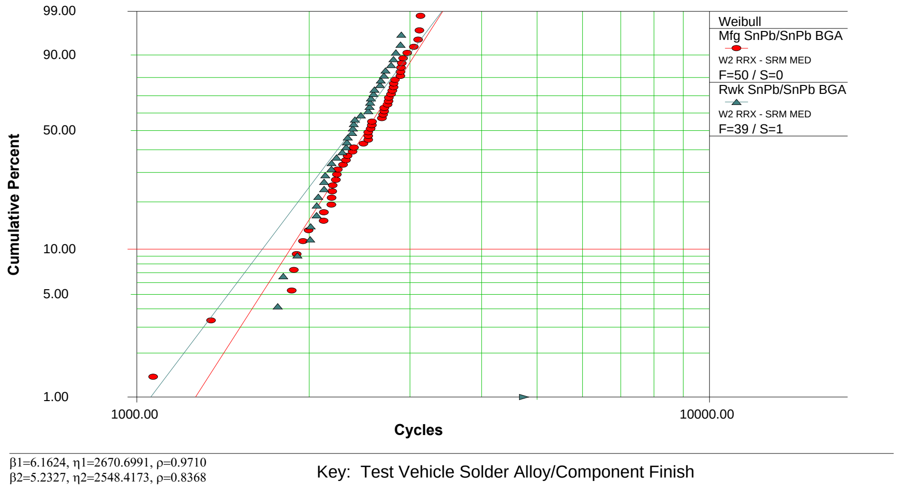


App Fig 82 TSOP-50 Un-Rework test results for the legacy ("Rework") test vehicles (140°C Tg)

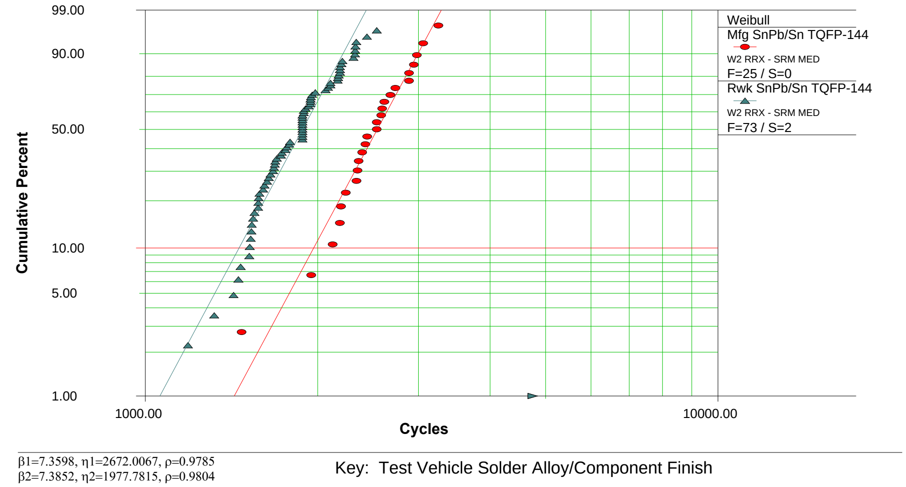


App Fig 81 TSOP-50 SnPb-SnPb test results for the legacy ("Rework") test vehicles (140°C Tg)

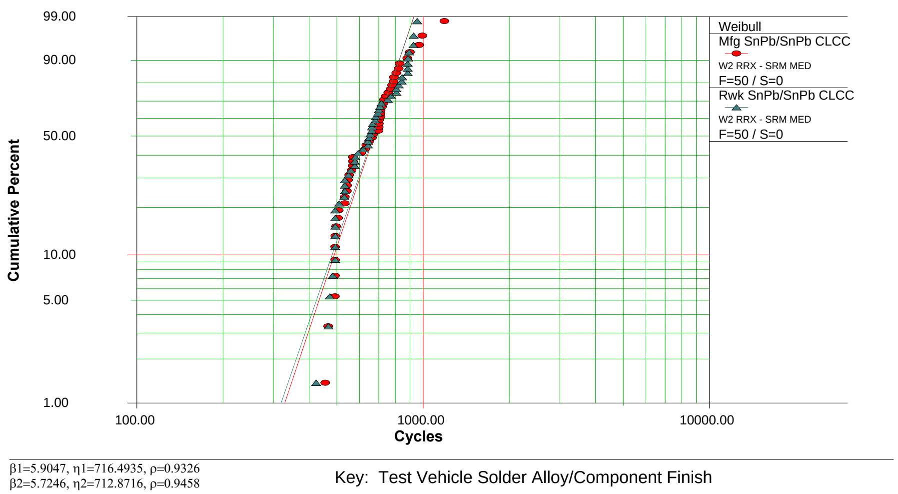
Appendix G Weibull Charts “Manufactured” vs. “Rework” Test Vehicles



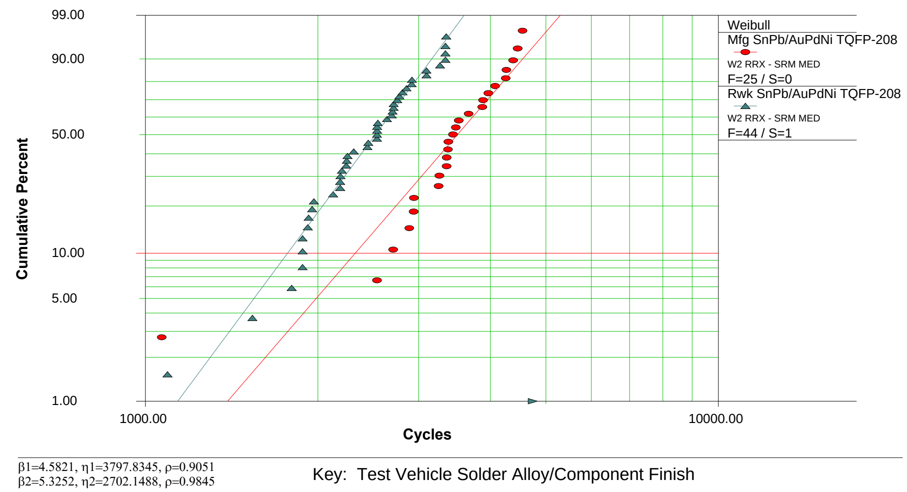
App Fig 83 BGA-225 SnPb-SnPb “Manufactured” versus legacy (“Rework”) test vehicles (170°C versus 140°C)



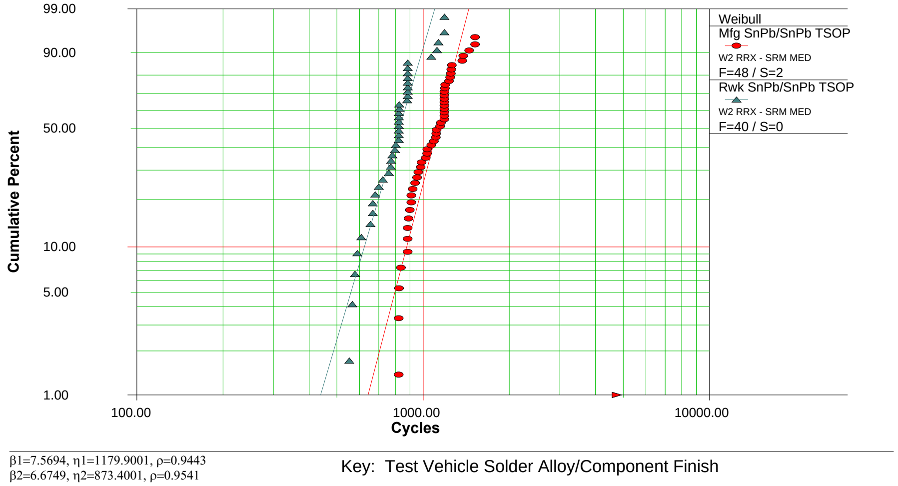
App Fig 85 TQFP-144 SnPb-SnPb “Manufactured” versus legacy (“Rework”) test vehicles (170°C versus 140°C)



App Fig 84 CLCC-20 SnPb-SnPb “Manufactured” versus legacy (“Rework”) test vehicles (170°C versus 140°C)



App Fig 86 TQFP-208 AuPdNi versus AuPdNi “Manufactured” versus legacy (“Rework”) test vehicles (170°C versus 140°C)



App Fig 87 TSOP-50 SnPb-SnPb "Manufactured" versus legacy ("Rework") test vehicles (170°C versus 140°C)